



**Institute For
Information
Storage
Technology**

University of Santa Clara

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Storage
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University of Santa Clara

LECTURE NOTES

**FOUR-DAY SHORT COURSE ON
INFORMATION STORAGE TECHNOLOGY**

MARCH 25 - 29, 1985

PRESENTED IN COOPERATION WITH

IEEE

CARNEGIE-MELLON UNIVERSITY - MTC
UNIVERSITY OF CALIFORNIA AT SAN DIEGO - CMRR
UNIVERSITY OF MINNESOTA - MINT

Institute For Information Storage Technology

University of Santa Clara

FOUR-DAY SHORT COURSE ON INFORMATION STORAGE TECHNOLOGY

GENERAL INFORMATION

DATES: Session I March 25 - 28, 1985 (Mon-Thurs)
 Session II March 26 - 29, 1985 (Tues-Fri)

CLASS HOURS: **8:30 a.m. to 4:30 p.m. each day**
 Includes Coffee Breaks and Lunch

RECEPTION: Wednesday, March 27th, 5:00 p.m. to 7:00 p.m.

LOCATION: Daly Science Center, Room 206 or 207
 University of Santa Clara, Santa Clara, California

FEE: \$650 — Includes Coffee Breaks, Lunches, Reception, and
 Course Notes.

Make check payable to "University of Santa Clara"

TO REGISTER: Mail registration form, with fee, to:

Institute for Information Storage Technology
University of Santa Clara
Suite 201
900 Lafayette Street
Santa Clara, CA 95050

LODGING: The University is located within five minutes of the San Jose International Airport.
Hotels in the vicinity include:
 Red Lion (408) 279-0600, (800) 547-8010,
 Hyatt House (408) 298-0300 or (800) 228-9000,
 Howard Johnsons (408) 287-7535 or (800) 654-2000.

Attendees will be expected to make their own hotel reservations.

For further information, phone (408) 984-4294.

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**FOUR-DAY SHORT COURSE ON
INFORMATION STORAGE TECHNOLOGY**

TOPICS AND SPEAKERS

Magnetism and Magnetic Recording Materials

The origin of magnetism, intrinsic and extrinsic properties of magnetic materials that determine their behavior in magnetic recording. Coercivity mechanisms, M-H loops and possible future developments in magnetic materials. Non-magnetic properties of materials and their importance.

Geoffrey Bate
Verbatim Corporation

The Physics of Magnetic Recording

The physics underlying the recording process, demagnetization and field equations. Analysis of the write and reproduce process, including reciprocity, temporal and frequency response, and magnetization pattern dependency.

Neal Bertram
Center for Magnetic Recording Research

Thin Magnetic Phenomena and Processes

Magnetic properties of thin films and their relation to microstructure. Domain phenomena in thin film heads, thin film head and media fabrication techniques. Magneto-resistive and magneto-optic phenomena.

Robert White
CDC

Magnetic Recording Heads

Theory and practice of magnetic heads, including: record gap; fields required as a function of gap length, wavelength and media coercivity; efficiency and record current estimation; saturation effects. Several types of magnetoresistive heads and head generated noise will be discussed.

Fred Jeffers
Kodak Research Laboratory

Analog Recording Systems and Noise

Physical origins of media, head and electronics noise, including expressions for the narrow-band and wide-band signal to tape noise ratios. The three main types of analog recording systems; audio, instrumentation and video; the use of ac bias, pre-equalization and post-equalization.

John Mallinson, UCSD
Center for Magnetic Recording Research

The Magnetic Recording Channel

Sources of noise in digital recording systems, linear and non-linear distortions, intersymbol interference, channel coding, equalization, detection, partial response, clock recovery, and linear versus tract density tradeoffs.

Mike Haynes
IBM

Optical Recording and Storage Media

Optical components, design aspects of optical recording systems and optical media. Read only, write once and erasable optical storage, applications and performance characteristics. Current product activities.

Allan Bell
IBM

Systems and Applications — Future Trends

Basic attributes of disk (rigid and flexible) and tape data storage devices. Cost/performance design tradeoffs. Comparison of alternative storage technologies in terms of applications. Technological trends and their potential significance to the nature of the data storage marketplace of the future.

Al Hoagland, SCU
Institute for Information Storage Technology

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(408) 984-4294

About the Institute:

The Institute has been recently established to meet the need for continuing education by engineers working in the field of data storage and to create a supply of trained students in the relevant technical areas. Mass storage is a high technology area that is absolutely critical to the current and future evolution of information processing systems. The perspectives addressed by the Institute are information storage needs, their engineering challenges, and close cooperation and interaction with industry.

The Institute is located in the heart of data storage activity ("Silicon Valley") and, thus, is able to profit from the innovative environment and expertise of this region and, in turn, play a direct contributing role in serving its technical community.

A major commitment has been made to the development and dissemination of teaching material and course offerings in the fields of information storage technologies and mass storage devices, an area where the University of Santa Clara has been the pioneer and intends to remain the leader.

This course is but one in a planned set of offerings to disseminate information on the current state of the art.

From Highway 17 or 680 - 280

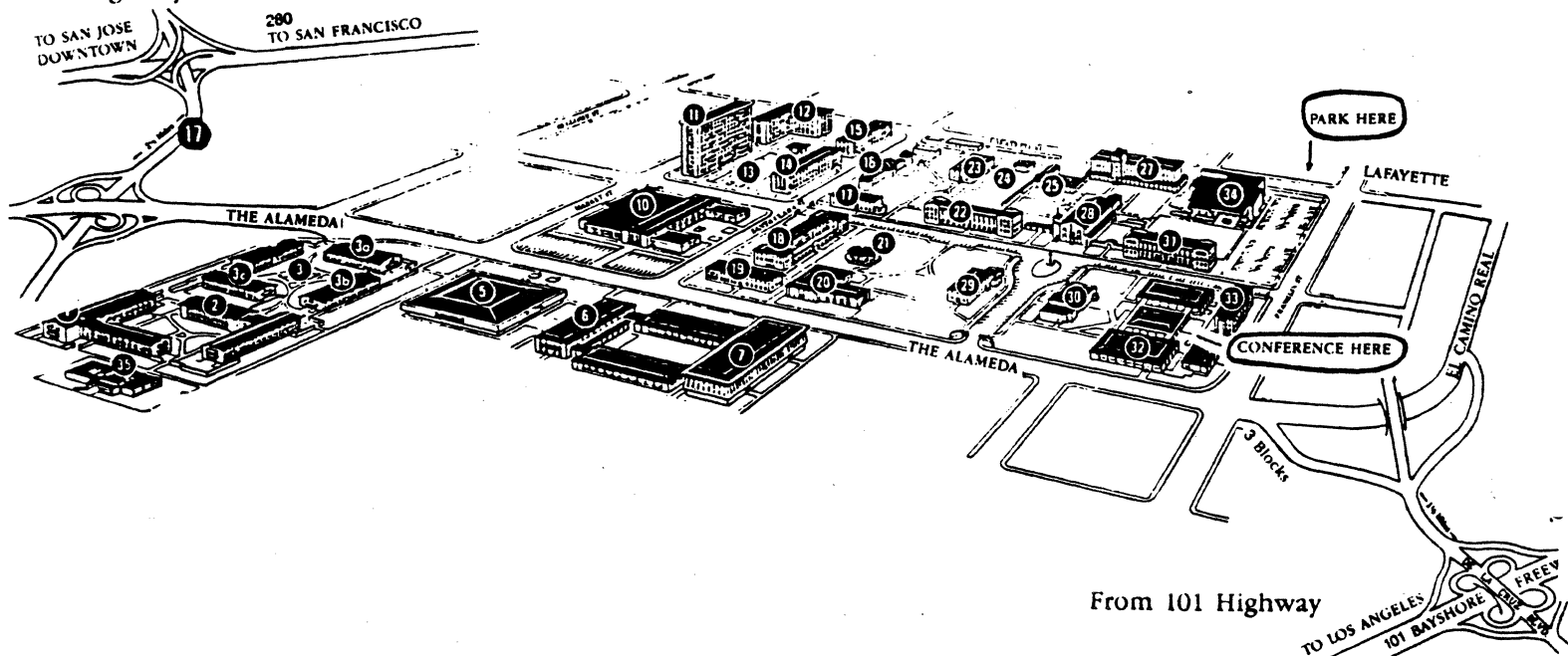


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Magnetism and Magnetic Recording Materials

**Geoffrey Bate
Verbatim Corporation**

MAGNETIC RECORDING MATERIALS

Origin of magnetism; electrons in motion

Diamagnetism, paramagnetism, ferromagnetism, ferrimagnetism and antiferromagnetism

Exchange interaction

Magnetic properties: intrinsic (M_s , K_1 , K_2 , Curie temperature)

Magnetic properties: extrinsic (M_r , H_c , permeability)

Domains and domain walls

The hysteresis loop

Single-domain particles

Shape, crystalline and strain anisotropy

MAGNETIC RECORDING MATERIALS

Orientation and disorientation

Modes of magnetization reversal in single-domain particles

Temperature-and-stress-dependence of magnetic properties

Preparation and properties of particles of:

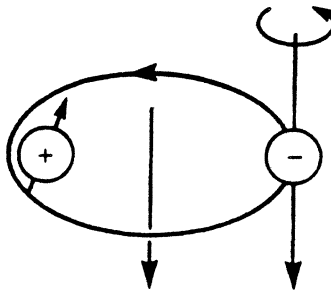
- $\gamma\text{-Fe}_2\text{O}_3$
 - CrO_2
 - cobalt-iron oxides
 - barium ferrite
 - metals
- preparation of thin films by:
- electroplating
 - chemical plating
 - sputtering

MAGNETIC RECORDING MATERIALS**Important non-magnetic properties of recording materials**

- particle loading
- coating thickness, smoothness
- particle size and surface area
- dispersion and uniformity
- reliability - freedom from defects
- durability
- coefficients of friction
- hardness and abrasivity
- resistivity
- transmissivity
- corrosion resistance

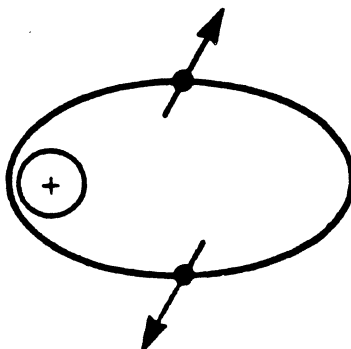
MAGNETISM

- A property of orbiting and spinning electrons



- Spin is more important than orbital motion

- in an isolated atom the orbital magnetic moment is usually larger than the moment arising from spin.
- a moment even smaller is associated with the nucleus.
- in a ferromagnetic solid the orbital moments of neighboring atoms interact through the crystal lattice ("quenched") leaving only the spin moments active.

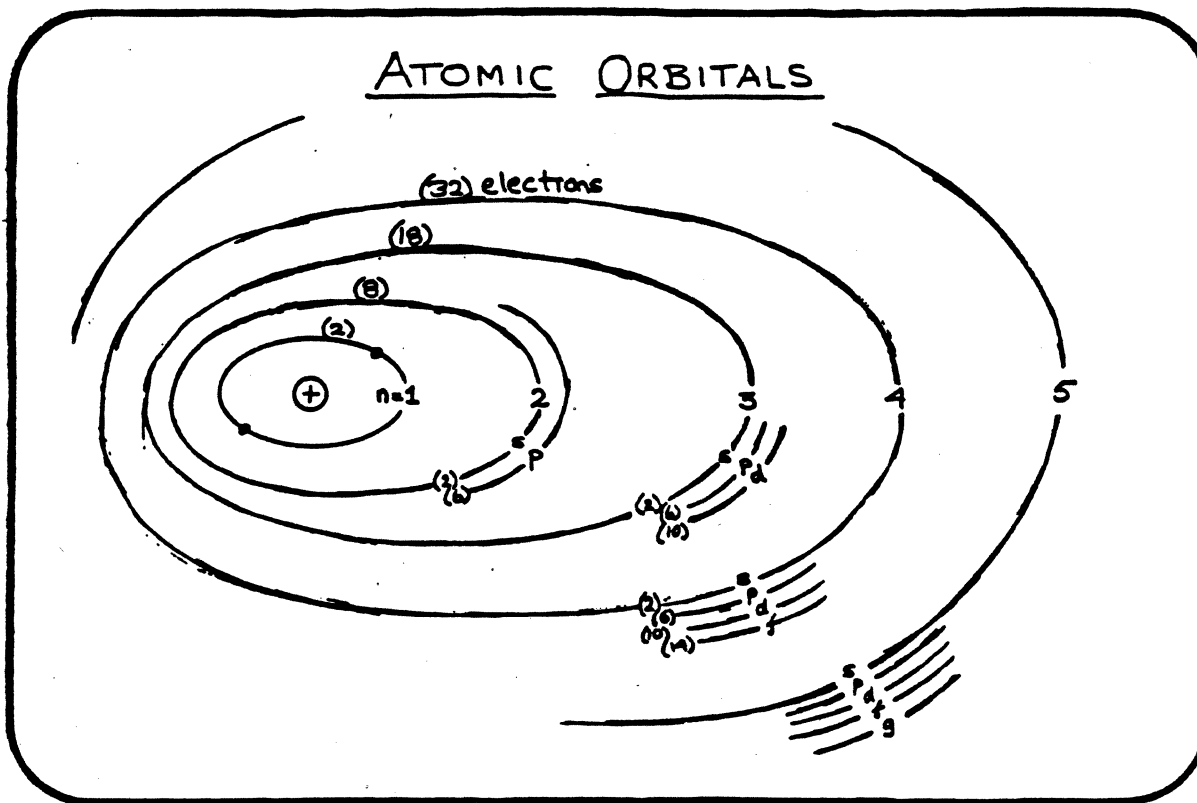


- **Electrons in same orbit have opposite spins**

- Pauli Exclusion Principle: if two electrons in an atom have the same principal quantum number
the same azimuthal quantum number
the same magnetic quantum number

→ then the spins must be opposed.

it is convenient though inaccurate, to regard an electron as a localized (point) charge. A more accurate, though less easily visualized, description is provided by wave mechanics and involves a cloud extending around the orbit in such a way that the local density of the cloud represents the possibility of finding the electron at that position.



- the application of the Pauli Exclusion Principle leads to a system of atomic orbits in which each orbit is associated with one or more orbitals.

- the first orbit holds a maximum of 2 electrons

2nd	"	"	"	"	8 electrons
3rd	"	"	"	"	18 electrons
4th	"	"	"	"	32 electrons
5th	"	"	"	"	50 electrons

-atom- -solid
maps
ms.

	K	L	M	N	O	P	Q	Ground	$\chi \times 10^6$
	1s	2s 2p	3s 3p 3d	4s 4p 4d 4f	5s 5p 5d	6s 6p 6d	7s	term	
H 1	1							$^2S_{1/2}$	-1.97
He 2	2							1S_0	-0.47
Li 3	2	1						$^2S_{1/2}$	+0.50
Be 4	2	2						1S_0	-1.00
B 5	2	2 1						$^2P_{3/2}$	-0.69
C 6	2	2 2						3P_0	-0.49
N 7	2	2 2 1						$^4S_{3/2}$	-0.8
O 8	2	2 4						3P_2	+108.2
F 9	2	2 5						$^4S_{3/2}$	-
Ne 10	2	2 6						1S_0	-0.23
Na 11			1					$^2S_{1/2}$	+0.51
Mg 12			2					1S_0	+0.55
Al 13		10	2 1					$^2P_{3/2}$	+0.65
Si 14		Ne core	2 2					3P_0	-0.13
P 15			2 3					$^4S_{3/2}$	-0.90
S 16			2 4					3P_2	-0.49
Cl 17			2 5					3P_2	-0.571
A 18	2	2 6	2 6					1S_0	-0.48
K 19				1				$^2S_{1/2}$	+0.52
Ca 20				2				1S_0	+1.10
Sc 21				1 2				$^2D_{3/2}$	-
Ti 22				2 2				3F_4	+1.25
V 23				3 2				$^4F_{3/2}$	+1.4
Cr 24				5 1				7S_3	+3.06
Mn 25				5 2				$^6S_{5/2}$	+11.8
Fe 26				6 2				5D_4	Fe core.
Co 27				7 2				5D_4	"
Ni 28				8 2				3F_4	"
Cu ⁺	2	2 6	2 6 10					1S_0	
Cu 29				1				$^2S_{1/2}$	-0.086
Zn 30				2				1S_0	-0.167
Ga 31				2 1				$^2P_{3/2}$	-0.24
Ge 32				2 2				3P_0	-0.13
As 33				2 3				$^4S_{3/2}$	-0.31
Se 34				2 4				3P_2	-0.32
Br 35				2 5				3P_2	-0.39
Kr 36	2	2 6	2 6 10	2 6				1S_0	-0.35
Rb 37					1			$^2S_{1/2}$	+0.21
Sr 38					2			1S_0	-0.20
Y 39					1 2			$^2D_{3/2}$	+5.3
Zr 40					2			3F_4	-0.45
Nb 41					1 1			$^2D_{3/2}$	+1.5
Mo 42					1 2			3F_4	+0.04
Mn 43					2			$^6S_{5/2}$	-
Ru 44					1			5D_4	+0.50
Rh 45					1			$^4F_{3/2}$	+1.11
Pd 46	2	2 6	2 6 10	2 6 10				1S_0	+5.4

TABLE II. Electronic configurations of the elements and mass susceptibility of with the exception

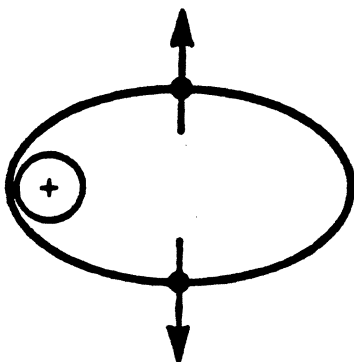
	K	L	M	N	O	P	Q	Ground	$\chi \times 10^6$
	1s	2s 2p	3s 3p 3d	4s 4p 4d 4f	5s 5p 5d	6s 6p 6d	7s	term	
Ag 47					1			$^2S_{1/2}$	-0.20
Cd 48					2			1S_0	-0.18
In 49					2 1			$^2P_{3/2}$	-0.11
Sn 50					2 2			3P_0	-0.25
Sb 51					2 3			$^4S_{3/2}$	-0.87
Te 52					2 4			3P_2	-0.31
I 53					2 5			$^2P_{3/2}$	-0.36
Xe 54	2	2 6	2 6 10	2 6 10	2 6			1S_0	-0.34
Cs 55						1		$^2S_{1/2}$	-0.22
Ba 56						2		1S_0	+0.9
La 57					Xe core	1		$^2D_{3/2}$	+1.04
Ce 58					Xe core	1 1		3F_4	+13.0
Pr 59						1 1		$^4F_{3/2}$	+25.0
Nd 60						1 1		$^6S_{5/2}$	+26.0
Pm 61						1		$^6S_{5/2}$	-
Sm 62						2		$^6S_{5/2}$	-
Eu 63						2		$^6S_{5/2}$	+22.0
Gd 64						2		8S_7	Fe core.
Tb 65						1 1		7F_6	-
Dy 66						1 1		7F_6	-
Ho 67						1 1		7F_6	-
Er 68						1 1		7F_6	-
Tm 69						2		$^6F_{5/2}$	-
Yb 70						2		$^6F_{5/2}$	-
Lu ⁺⁺⁺	2	2 6	2 6 10	2 6 10 14	2 6			1S_0	-
La 71						1		$^2D_{3/2}$	-
Hf 72						2		$^2D_{3/2}$	-
Ta 73						3		$^2D_{3/2}$	+0.57
W 74						4		$^2D_{3/2}$	+0.26
Re 75						5		$^2D_{3/2}$	-
Os 76						6		$^2D_{3/2}$	+0.65
Ir 77						7		$^2D_{3/2}$	+0.15
Pt 78						8		$^2D_{3/2}$	+1.10
Au ⁺	2	2 6	2 6 10	2 6 10 14	2 6 10			1S_0	-
Au 79						1		$^2S_{1/2}$	-0.15
Hg 80						2		1S_0	-0.106
Tl 81						2 1		$^2P_{3/2}$	-0.24
Pb 82						2 2		3P_0	-0.12
Bi 83						2 3		$^4S_{3/2}$	-1.25
Po 84						2 4		3P_2	-
— 85						2 5		3P_2	-
Rn 86	2	2 6	2 6 10	2 6 10 14	2 6 10	2 6		1S_0	-
— 87							1	$^2S_{1/2}$	-
Ra 88							2	1S_0	-
Ac 89							2	$^2D_{3/2}$	+0.11
Th 90							2	3F_4	+2.6
Pa 91							3	3F_4	-
U 92							4	3F_4	-

bulk material. All the ground terms given have been derived from experiment of those in brackets.

from "Modern Magnetism"
L.F. Bates

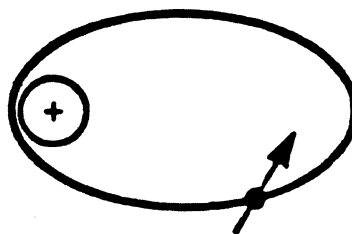
TYPES OF MAGNETISM

Diamagnetic



$$m = 0$$

Paramagnetic



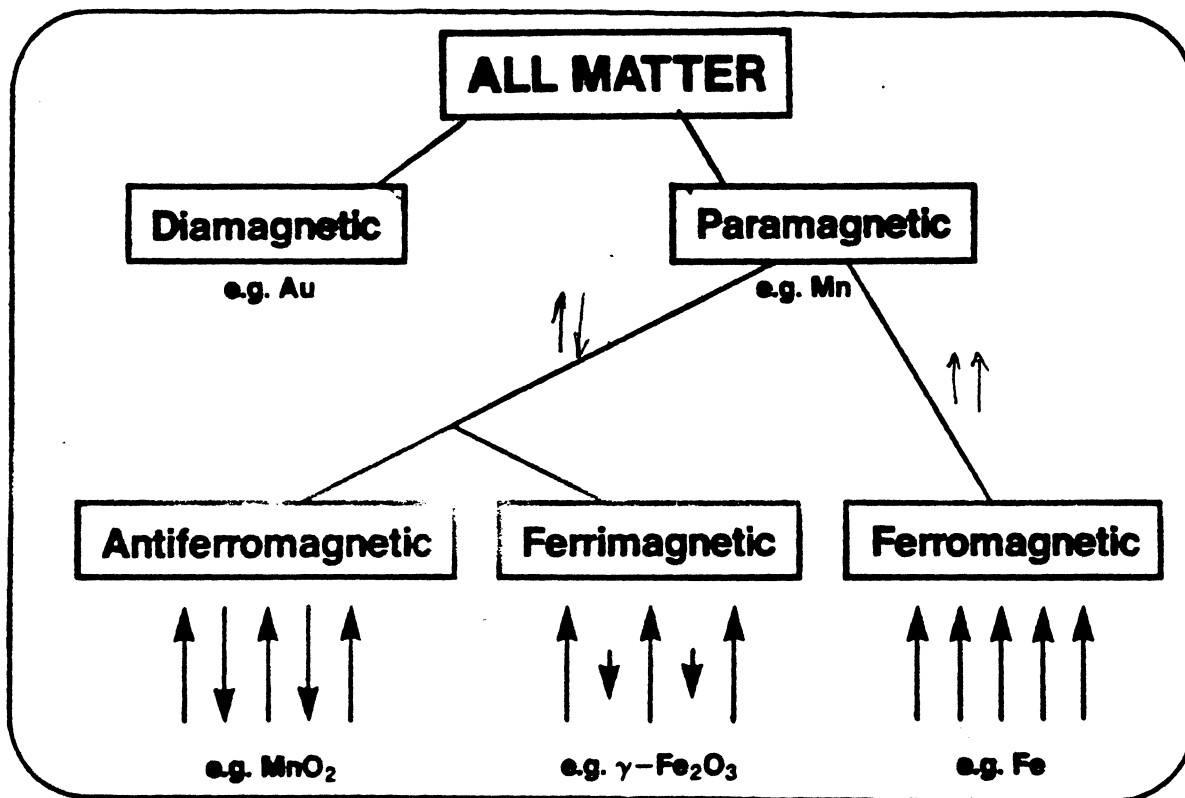
$$m \neq 0$$

Diamagnetism: an even number of electrons present

- they fill up the orbitals in order
1s, 2s, 2p, 3s, 3p, 3d, 4s, 4p, 4d, etc
- no net atomic moment

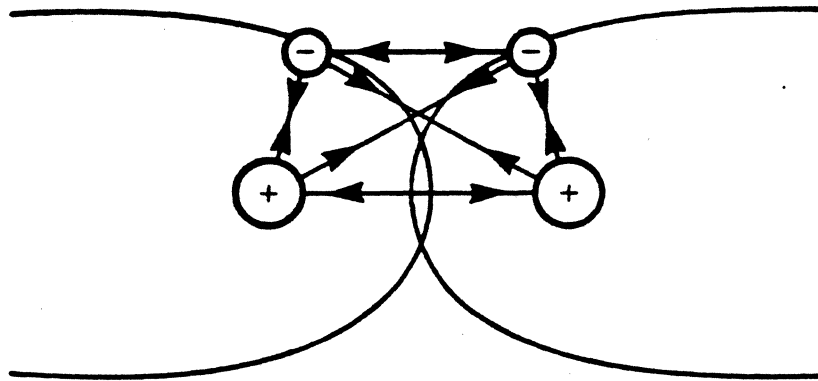
Paramagnetism: an odd number of electrons

- permanent atomic moment



- Coupling between adjacent atomic moments may be parallel → ferromagnetism
antiparallel → antiferromagnetism, ferrimagnetism.
- Only FERROMAGNETICS AND FERRIMAGNETICS possess a spontaneous magnetic moment i.e., the magnetization persists even when the applied field is reduced to zero.

EXCHANGE INTERACTION



Classical Interactions

Interactions between electrons and nuclei are attractive

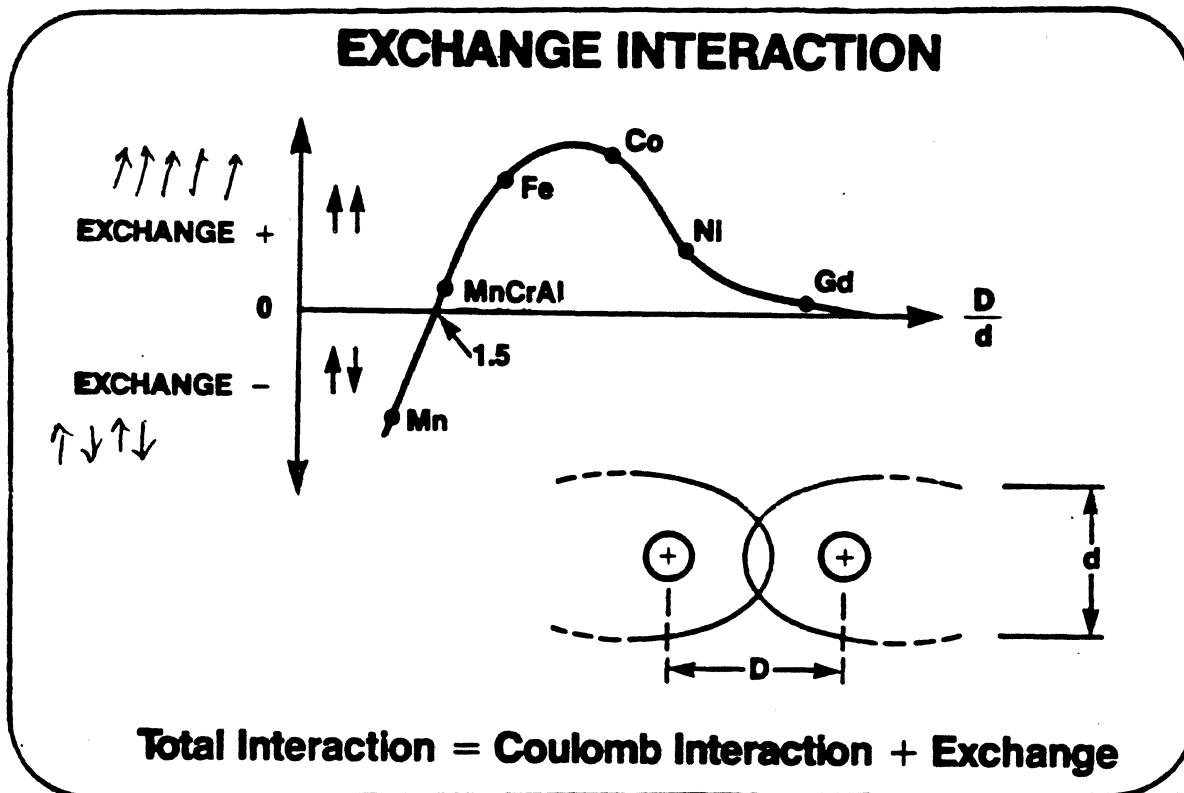
Interactions between electrons and electrons
nuclei and nuclei } are repulsive

- these are the COLOUMB INTERACTIONS

Quantum Mechanical Interactions

Interactions between part of one electron (probability density) cloud with part of another electron cloud OR with another part of the same cloud.

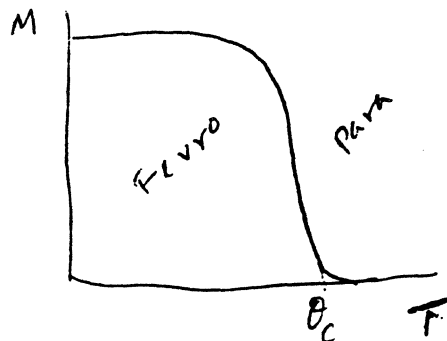
- this is EXCHANGE INTERACTION



John
Slater
(MST)

P/d	Cr	Mn	Fe	Co	Ni	Gd
	1.45	1.97	1.63	1.82	1.97	3.1
$\theta_c^\circ K$	/	/	1043	1400	631	287
$\theta_N^\circ K$	475	100				

- Ratio of interatomic spacing to atomic diameter must be greater than 1.5 for positive exchange and Ferromagnetism.



Curie temp gives more
info. on the strength of
the mag.

Thermal disordering = ordering force of the solid = θ_c .

MAGNETIC PROPERTIES

Intrinsic

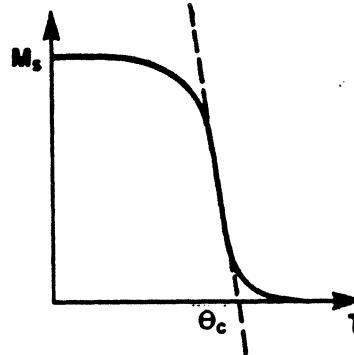
saturation magnetization, M_s

Curie temperature, θ_c

magneto-crystalline anisotropy, K_1, K_2

magnetostriction λ

$$\mathbf{B} = \mathbf{H} + 4 \pi \mathbf{M}_s$$



INTRINSIC PROPERTIES DEPEND ONLY ON:

- the type of atom e.g., Fe^{2+} , Fe^{3+} , Ni, Mn
- the number of atoms
- their arrangement in the crystal
- and the temperature

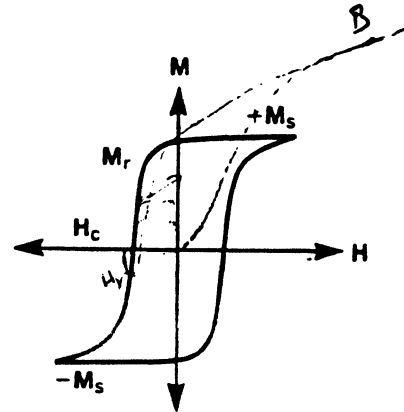
MAGNETIC PROPERTIES

Extrinsic

remanent magnetization M_r

coercivity H_c

permeability



EXTRINSIC PROPERTIES also depend on:

- the type, number, arrangement of the atoms
- and the temperature

but also depend on-

the shape and size of the sample

and its previous history

Handwritten note:
 $H_{rem} \rightarrow$ zero mag. field
 (even after coercivity
 field is applied the
 mag. is not zero)

$$B = H + 4\pi M$$

gauss oe emu/cc

$$M = 1 + 4\pi K$$

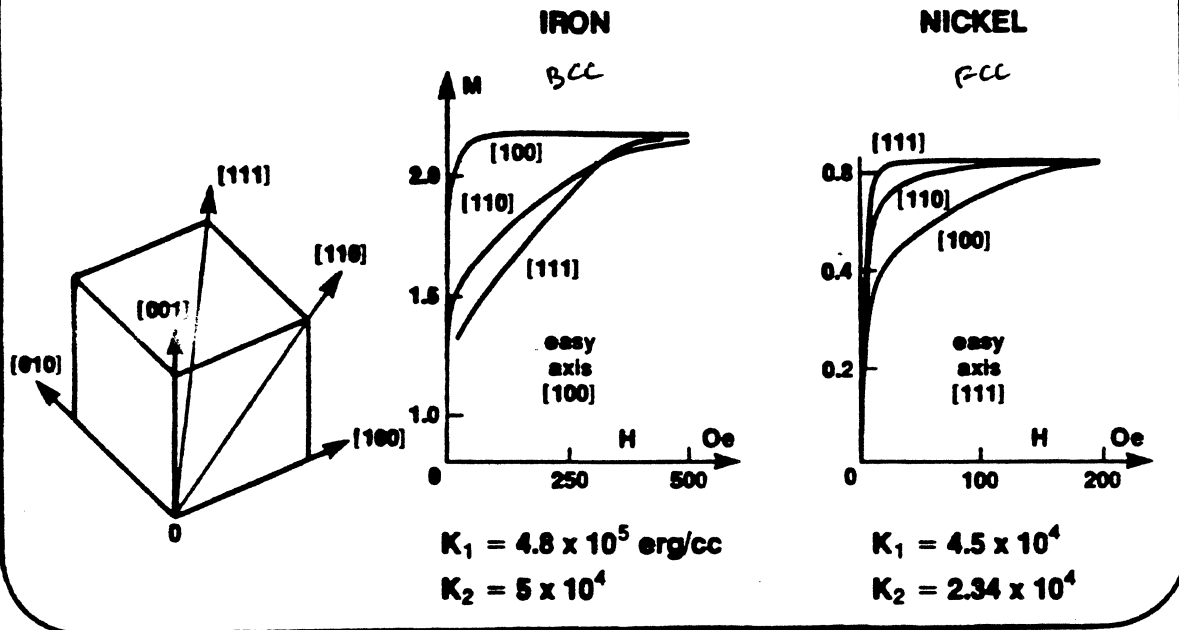
$\uparrow$ permeability $\uparrow$ vol. sus.

**SATURATION MAGNETIZATION (M_s)
in a magnetic field of 100 oersteds**

Diamagnetic e.g. Au	-4×10^{-3} emu/cc
Paramagnetic e.g. Mn	$+10^{-1}$
Antiferromagnetic e.g. MnO_2	$+10^{-1}$
Ferrimagnetic e.g. $\gamma\text{-Fe}_2\text{O}_3$	+400
Ferromagnetic e.g. Fe	+1700

- Only ferromagnetics and ferrimagnetics have magnetizations large enough to be technically interesting.

MAGNETO-CRYSTALLINE ANISOTROPY Iron And Nickel



$[100], [010]$

$[111] = \langle 100 \rangle$

$$\text{Cryst Energy} = K_0 + K_1 (\alpha_1^2 \alpha_2^2 + \alpha_2^2 \alpha_1^2 + \alpha_3^2 \alpha_1^2) + K_2 (\alpha_1^2 \alpha_2^2 \alpha_3^2) + K(\alpha) + \dots$$

Single crystals show anisotropic magnetism curves i.e. it is easier to magnetize them along some crystal directions than others. In iron the easy directions are the cube edges, in nickel the easy directions are the body diagonals.

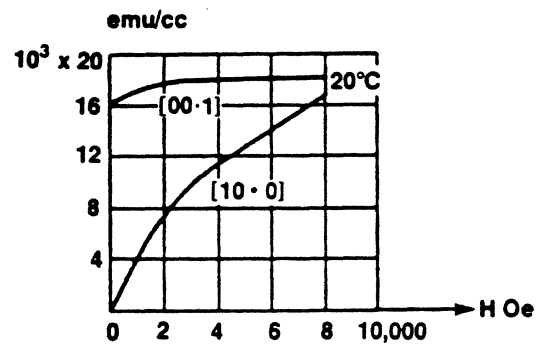
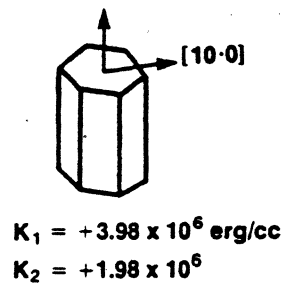
Rotating the magnetism from one easy direction to another involves rotating through a HARD direction.

$$\alpha_1 = \angle \text{field to } 100$$

$$\alpha_2 = \angle \text{field to } 110$$

$$\alpha_3 = \angle \text{field to } 111$$

COBALT



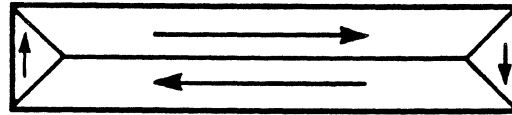
Cobalt has a hexagonal crystal structure and the easy axis of magnetization is along the hexagonal axis.

The magnitude of the magnetocrystalline anisotropy constant K , in cobalt is 10x larger than in iron and 100x larger than in nickel.

MAGNETIC DOMAINS

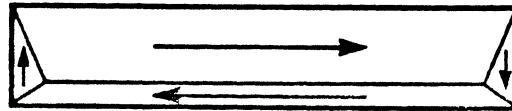
postulated to explain
why a piece of iron

$$\begin{aligned} H &= 0 \\ M &= 0 \end{aligned}$$



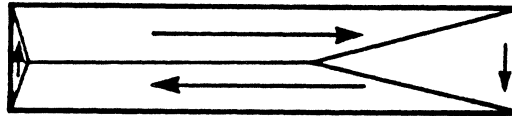
—may not be magnetized

$$\begin{aligned} H &\rightarrow \\ M &\rightarrow \end{aligned}$$



—may then be fully magnetized in small fields

$$\begin{aligned} H &\downarrow \\ M &\downarrow \end{aligned}$$



If the force holding spins parallel in a ferromagnetic material were of magnetic origin the internal field would need to be $\sim 10^7$ oersteds!

How then could the magnetization of a piece of iron be changed by the application of 100 oersteds?

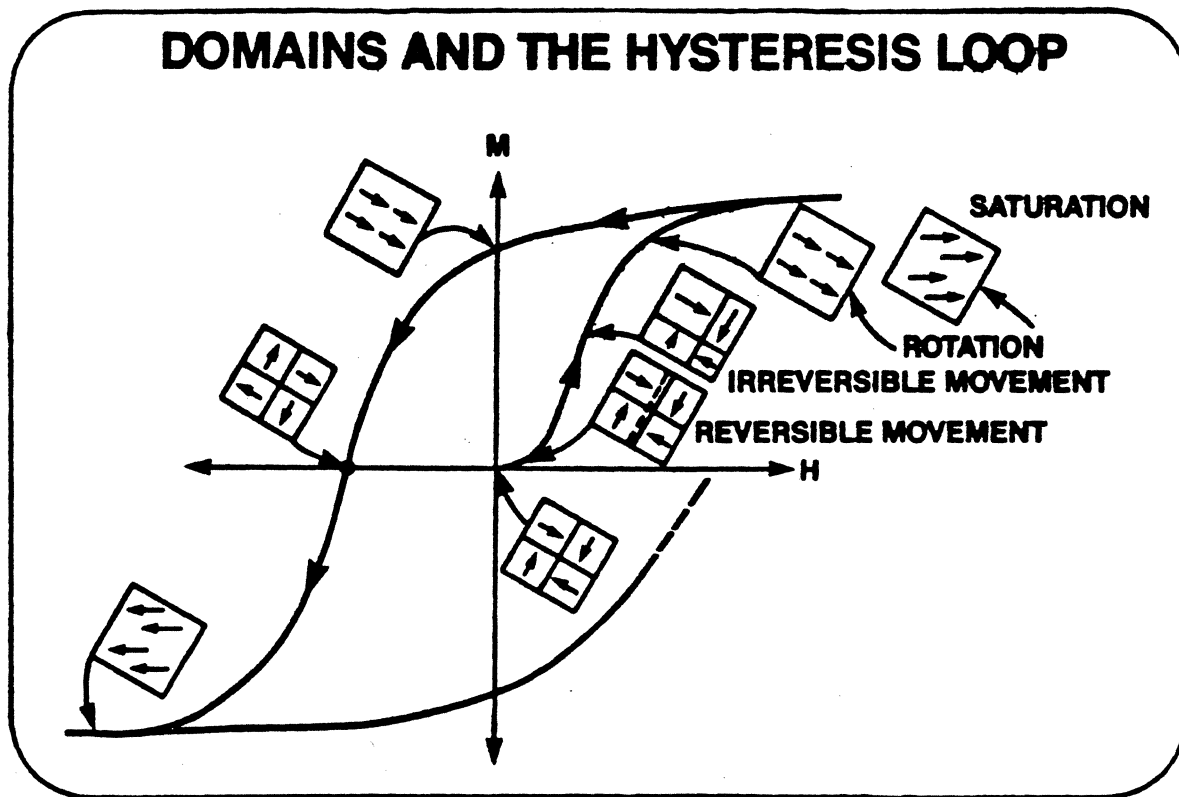
ANSWER: Magnetic domains

A piece of ferromagnetic material spontaneously divides into domains to reduce its magnetostatic energy.

Domain walls are about $1,000 \text{ \AA}$ thick or ~ 200 atomic spacings

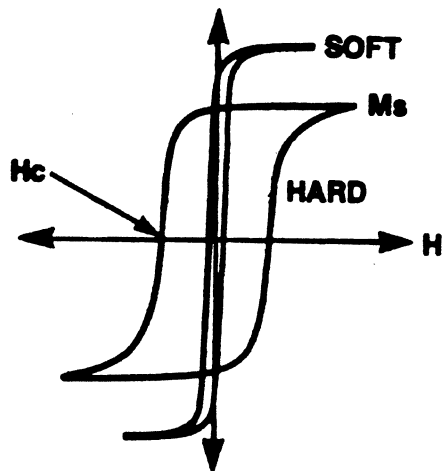
Domain wall energy is proportional to the wall area

DOMAINS AND THE HYSTERESIS LOOP



Domains are separated by domain walls. As the applied magnetic field changes the domain walls move to minimize the total magnetic energy.

HARD AND SOFT MAGNETIC MATERIALS



Soft:

pure Fe
80 Ni: 20 Fe
Mn Zn ferrite

Hard:

Particles $\gamma\text{-Fe}_2\text{O}_3$
 $\text{BaO} \cdot 0.6\text{Fe}_2\text{O}_3$
 SmCo_5

$\text{Fe}_{14}\text{Nb}_2\text{B}$

Practically important magnetic materials are usually either magnetically soft i.e. low remanence and coercivity, high permeability e.g. transformer laminations and recording heads.

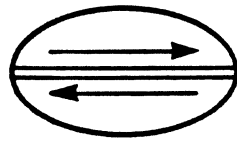
or magnetically hard i.e. high remanence and coercivity, low permeability e.g. permanent magnets and recording materials.

HARD AND SOFT MAGNETIC MATERIALS

<u>Soft</u>	<u>High Ms</u>	<u>Low H_c</u>	<u>Low Mr</u>	<u>High μ</u>
Fe	1700 emu/cc	1 Oe	<500 emu/cc	20,000
80Ni20Fe	660	0.1	<300	50,000
MnZn ferrite	400	0.02	<200	5,000

<u>Hard</u>	<u>High Ms</u>	<u>High H_c</u>	<u>High Mr</u>
γ -Fe ₂ O ₃	400	300-450	200-300
BaO.6Fe ₂ O ₃	360	2000-3000	180
SmCo ₅		24,000	

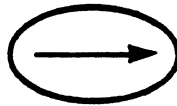
HARD MAGNETIC MATERIALS



$\longleftrightarrow 5\mu \longrightarrow$

MULTI-DOMAIN

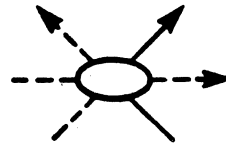
$H_C < 100 \text{ Oe}$



$\longleftrightarrow < 1\mu \longrightarrow$

SINGLE DOMAIN

$H_C = 100 - 3000$



$\longleftrightarrow < 0.02\mu \longrightarrow$

SUPERPARAMAGNETIC

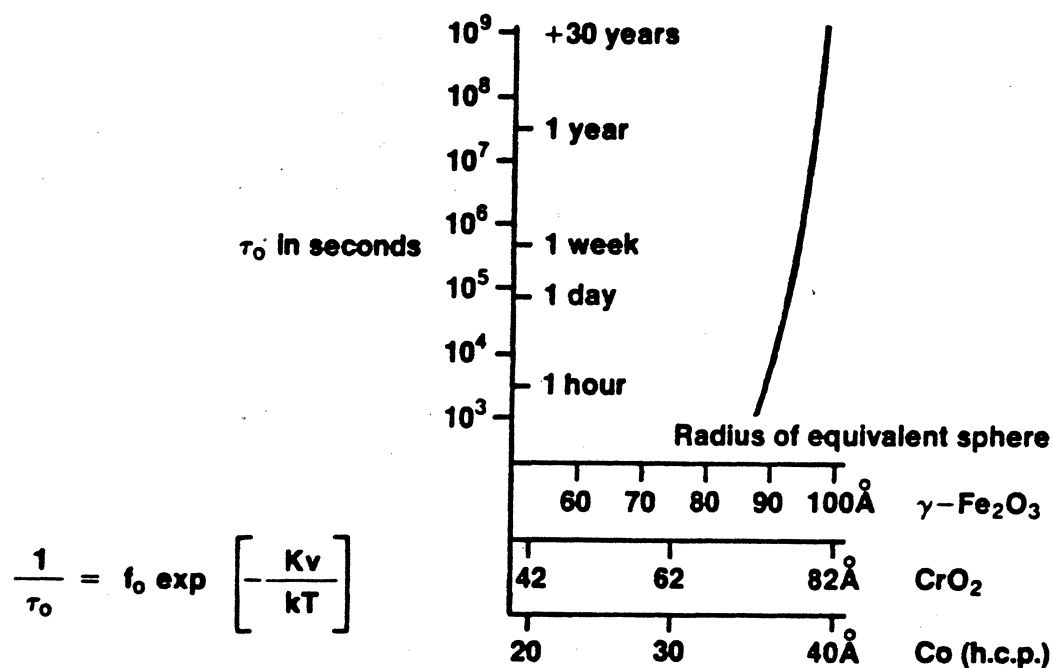
$H_C = 0$

Particles larger than $\sim 2\mu\text{m}$ usually have domain walls i.e., they are multi-domains (low H , low M_r)

Particles: $< 1\mu$ and $< 0.02\mu$ are single domains (high H_C , high M_r)

Particles: $< 0.02\mu$ are unstable

RELAXATION TIME FOR ACICULAR PARTICLES



The change from stable single domain behavior to unstable super-paramagnetic occurs with a reduction of less than a factor of 2 in particle volume!

SINGLE DOMAIN PARTICLES

Anisotropy

Maximum Coercivity

Crystalline

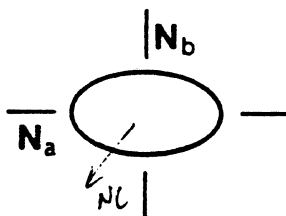
$$H_c = \frac{2 k_1}{M_s}$$

Strain

$$H_c = \frac{3 \lambda_s T}{M_s}$$

→ tension or compression

Shape



$$H_c = (N_b - N_a) M_s$$

$$N_a + N_b + N_c = 4\pi$$

- Single domain particles in which crystalline anisotropy or strain anisotropy dominates have coercivity inversely proportional to magnetization.
- Particles in which shape anisotropy dominates have coercivity directly proportional to magnetization.

N → demag. factor

SINGLE DOMAIN PARTICLES

Maximum Coercivity

	Iron	Cobalt	Nickel	$\gamma\text{-Fe}_2\text{O}_3$
Crystalline	250	3,000	70	230
Strain	300	300	2,000	<10
Shape (10:1)	5,300	4,400	1,550	2,450

*in practice
~300 Oe*
*low from shape
(low from cryst.)*

- In iron particles shape anisotropy is most likely to give high H_c
- In cobalt particles crystalline anisotropy is most likely to give high H_c
- In $\gamma\text{-Fe}_2\text{O}_3$ particles used in tapes and disks

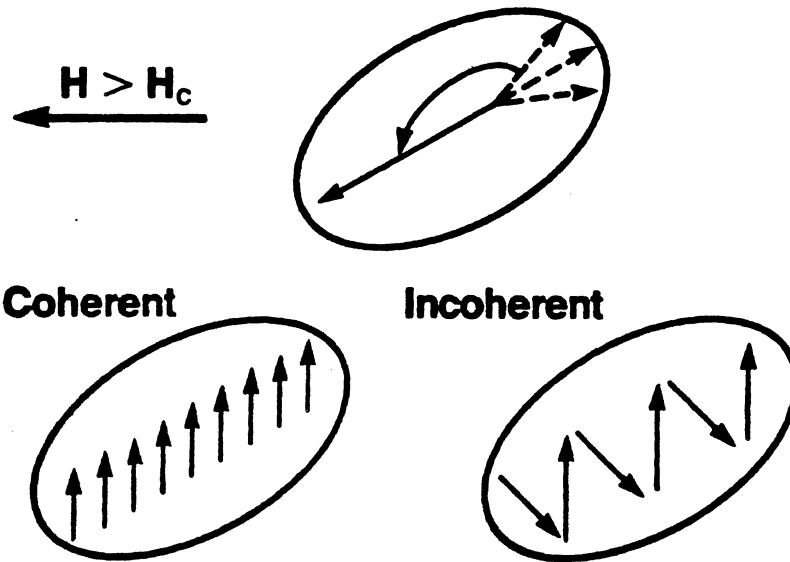
$\frac{2}{3} H_c$ attributable to the particles' shape.

$\frac{1}{3} H_c$ attributable to crystalline anisotropy.

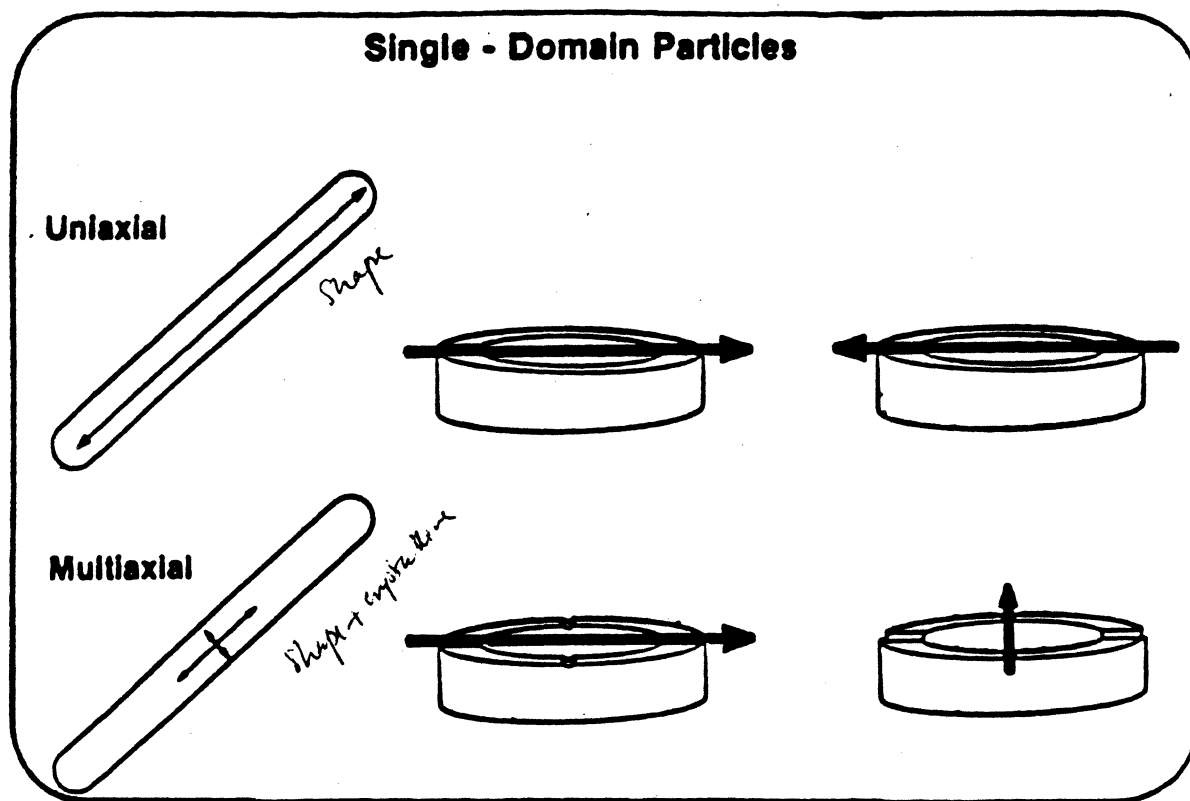
- Problem is the predicted value of coercivity for $\gamma\text{-Fe}_2\text{O}_3$ particles is about 10x too high.

*as attributed $\gamma\text{-Fe}_2\text{O}_3$
 $\Rightarrow$ be
 ~200 from shape anisotropy
 ~400 from crystalline anisotropy
 1-1000 $\Rightarrow$ increment made of reversal*

MAGNETIZATION REVERSAL

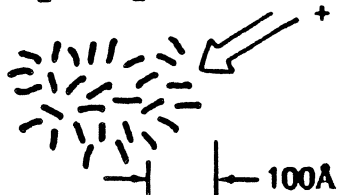


- Coherent rotation predicts values of H_c that are generally much too high.
- Most single domains (including $\gamma\text{-Fe}_2\text{O}_3$) reverse their magnetization incoherently.
- Coercivity is a most important property in recording materials since it expresses the ability of the material to resist accidental demagnetization and self demagnetization. In general, the higher the recording density the higher must be the coercivity.

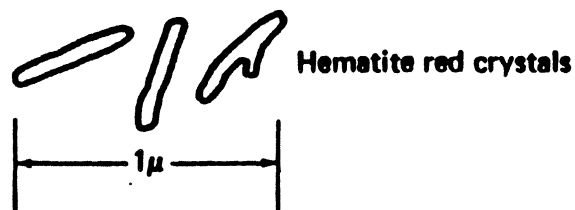
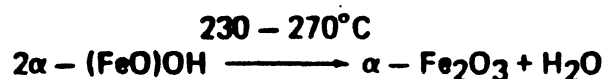


Acicular $\gamma - \text{Fe}_2\text{O}_3$

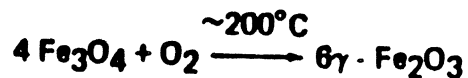
Step 1 Preparation of colloidal $\alpha - (\text{FeO})\text{OH}$
— goethite



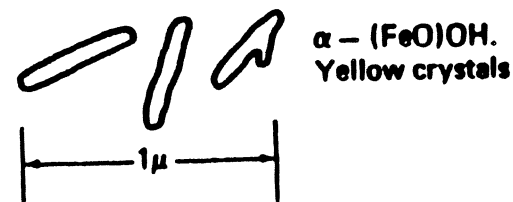
Step 3 Dehydrate



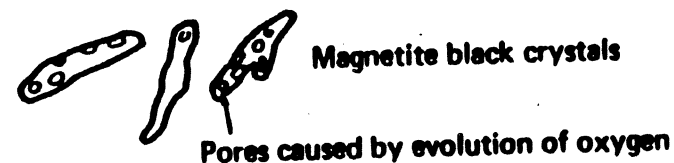
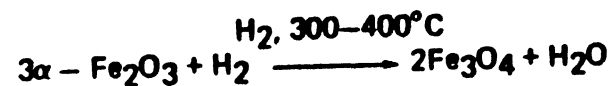
Step 5 Carefully re-oxidize



Step 2 use these as seeds to grow larger crystals of $\alpha - (\text{FeO})\text{OH}$ with water, scrap iron, air, 60°C , 4 hours.

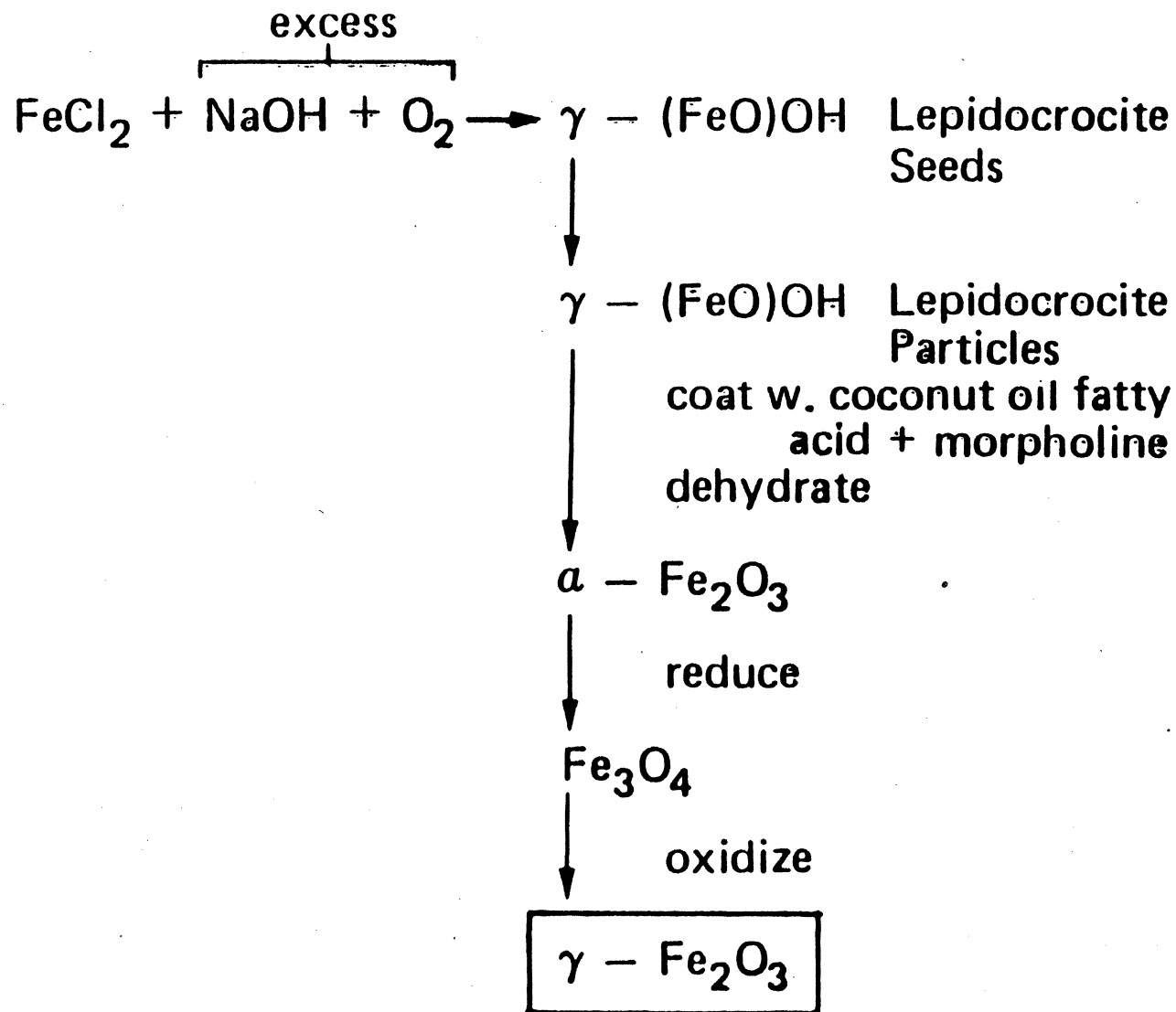


Step 4 Reduce



Transformations

Pigment $\rightarrow$ dehydrated oxide $\rightarrow$ magnetite $\rightarrow$ maghemite
 $[\alpha - (\text{FeO})\text{OH}] \quad [\alpha - \text{Fe}_2\text{O}_3] \quad [\text{Fe}_3\text{O}_4] \quad [\gamma - \text{Fe}_2\text{O}_3]$
 — are Pseudomorphic

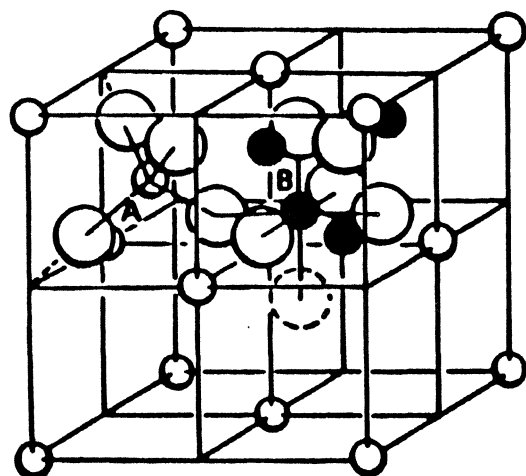


$\gamma - \text{Fe}_2\text{O}_3$, 2228 Process

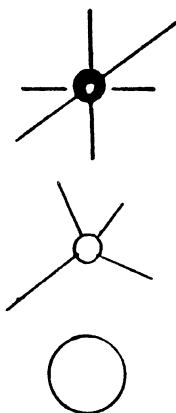
- More Acicular $H_c \sim 320 \text{ Oe}$, $\sigma_s = 74 \text{ emu/g}$.
- Fewer Dendrites
- Better Dispersion, orientation (2.9)

3/11/82

INTRINSIC MAGNETIC PROPERTIES OF Fe_3O_4 AND $\gamma\text{-Fe}_2\text{O}_3$



SPINEL STRUCTURE



INVERSE SPINEL

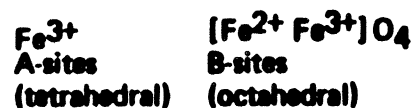
Fe^{2+} AND Fe^{3+} OCTAHEDRAL SITES

Fe^{3+} , TETRAHEDRAL SITES

OXYGEN

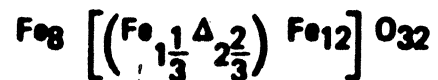
$$\text{OCTAHEDRAL SITES} = 16, \quad \text{TETRAHEDRAL SITES} = (8 \times \frac{1}{8}) + (6 \times \frac{1}{2}) + 4 = 8$$

Magnetite – inverse spinel



γ – Ferric Oxide – same oxygen sublattice

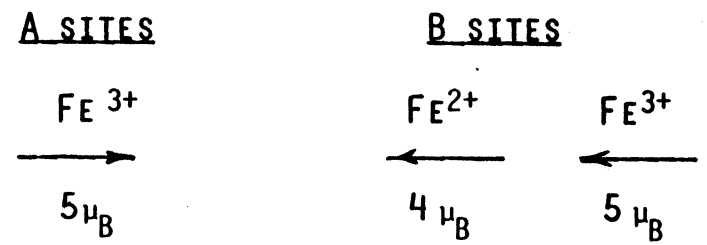
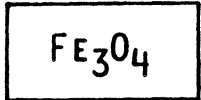
– vacancies arranged on a tetragonal superlattice ($c/a = 3$)



is the formula for $\frac{1}{3}$ unit cell.

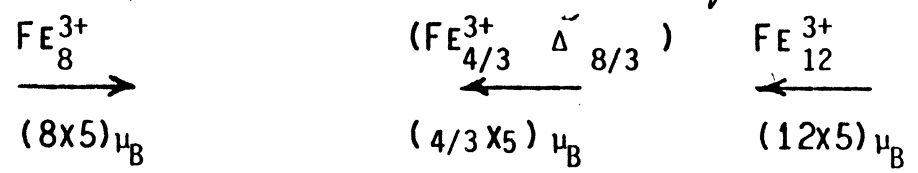
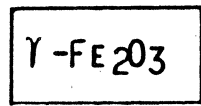
	Fe_3O_4	$\gamma\text{-Fe}_2\text{O}_3$
Moment per molecule	4 β	2.5 β
σ_{50}	97 emu/g	82 emu/g
σ_s	87 emu/g	74 emu/g
Density	5.197 g/cc	5.074 g/cc
I_s	453 emu/cc	400 emu/cc
Curie temperature	575°C	590°C
Anisotropy constant		
	$K_1 = -1.10 \times 10^5 \text{ erg/cc}$	$= -4.64 \times 10^4 \text{ erg/cc}$
	$\langle 111 \rangle$ easy	$\langle 110 \rangle$ easy
	$\langle 100 \rangle$ hard	$\langle 100 \rangle$ hard

INTRINSIC PROPERTIES: $\gamma\text{-Fe}_2\text{O}_3 \cdot \text{Fe}_3\text{O}_4$



NET MOMENT = $4\mu_B$ PER FORMULA UNIT

$\sigma_0 = \frac{5585}{M} n_B$; $M = 231.6$. $\therefore \sigma_0 = 97 \text{ EMU/G}$ (EXPT = 94 EMU/G)



NET MOMENT = $(16/3 \times 5)\mu_B$

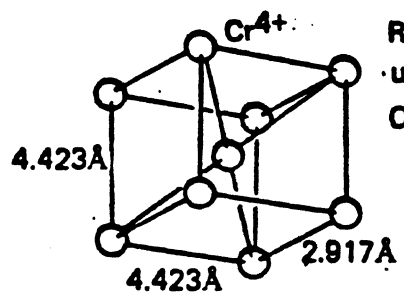
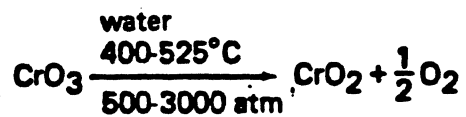
MOMENT PER FORMULA UNIT = $3/32 \times 16/3 \times 5\mu_B = 2.5\mu_B$

OR 1.25 μ /IRON ATOM: EXPT = 1.18

$\sigma_0 = 82 \text{ EMU/G}$

$\sigma_0 = 74 \text{ EMU/G}$; EXPERIMENT

2000 30 μ

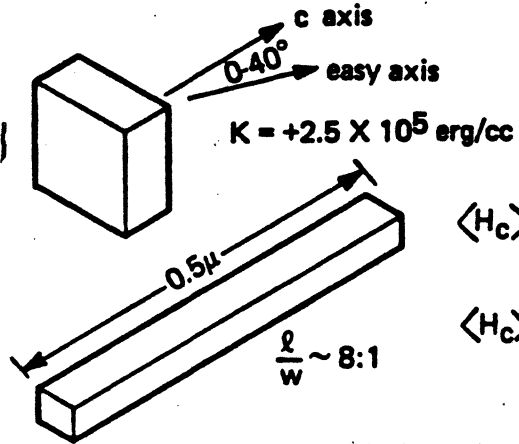
Chromium Dioxide**Rutile structure**

unit cell has two formula units

Oxygen at $(\bar{u}, \bar{u}, o)$ (u, u, o) $(u - \frac{1}{2}, \frac{1}{2} - u, \frac{1}{2})$ $(\frac{1}{2} - u, u - \frac{1}{2}, \frac{1}{2})$

CHROMIUM DIOXIDE HAS TETRAGONAL SYMMETRY

Chromium Dioxide *- ferro mag.*



$$K = +2.5 \times 10^5 \text{ erg/cc}$$

$$\langle H_c \rangle^{\text{crystal}} = 0.96 \frac{K}{M_s} = 585 \text{ oe}$$

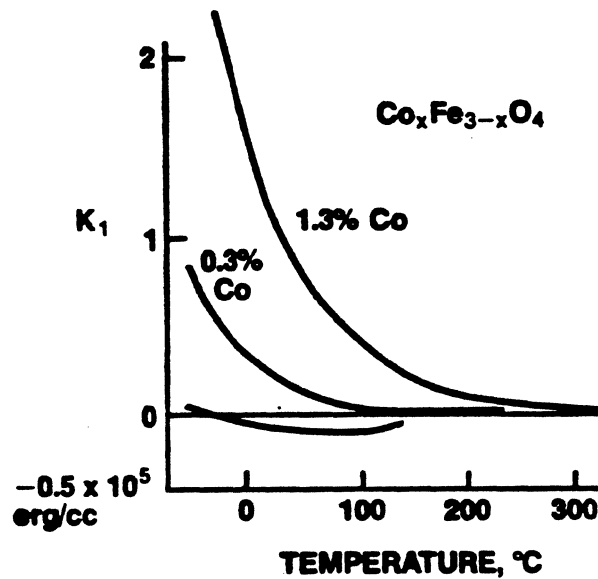
$$\begin{aligned} \langle H_c \rangle^{\text{shape}} &= 0.18\pi M_s (6K_n - 4L_n) \\ &= 590 \text{ oe} \end{aligned}$$

Temperature independence of $H_c \rightarrow$ shape anisotropy
rotational hysteresis $\rightarrow$ incoherent rotation

COBALT-DOPED IRON OXIDES

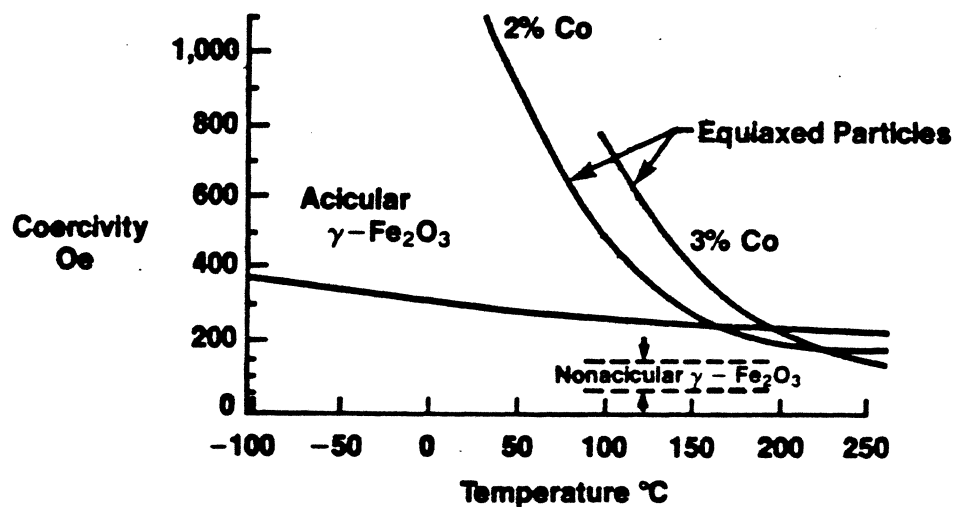
$$H_c = 0.64 \frac{K_1}{M_s}$$

H_c and M_r
depend on:
temperature
time
stress



- Increasing the H_c of iron oxide particles by increasing their shape anisotropy is not very effective
- Adding 2-3% cobalt helps by adding a magneto-crystalline contribution to the coercivity.

TEMPERATURE-DEPENDENCE OF COERCIVITY



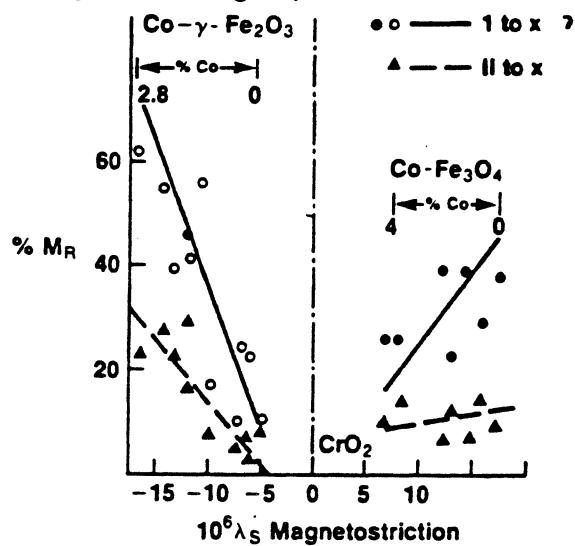
The price paid for doping with cobalt is an increased sensitivity of coercivity to temperature.

- cobalt-doped particles tend to lose their elongated shape.

REMANENCE LOSS IN COBALT-SUBSTITUTED $\gamma - \text{Fe}_2\text{O}_3$ and Fe_3O_4

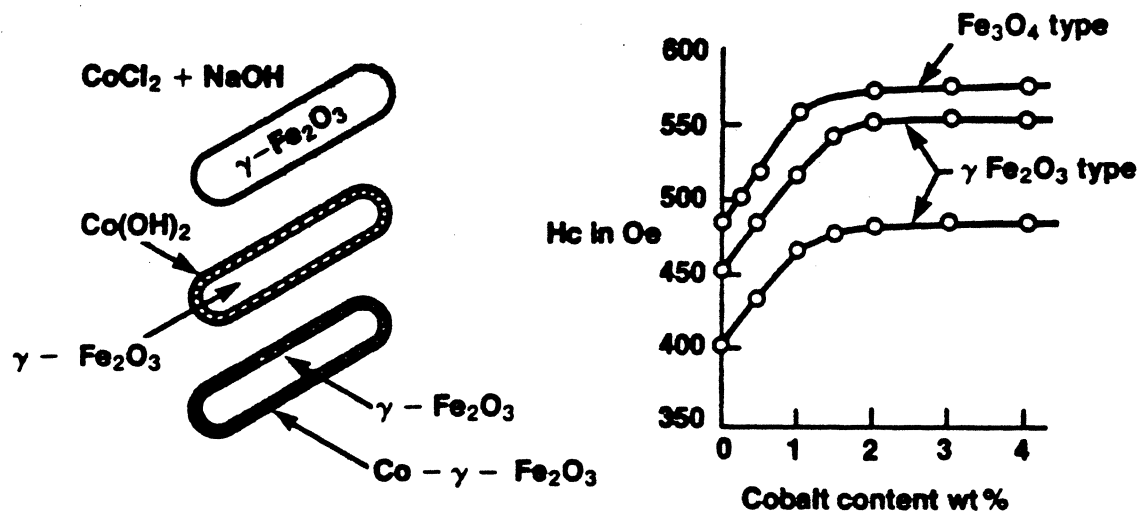
1 kg/s impact on
 0.2 cm^2

• • longitudinal M
▲ transverse M



- Sensivity to strain also depends on the cobalt content and on the crystal structure.
- The parameter linking strain and magnetization is Magnetostriction.

COBALT-IMPREGNATED IRON OXIDE



*1. D.L. → J.A.
considerable
γ-Fe₂O₃
max well - XL*

- Coercivity can be increased without making particles unusably sensitive to temperature by impregnating the surface with cobalt.

PARTICLE DEVELOPMENTS

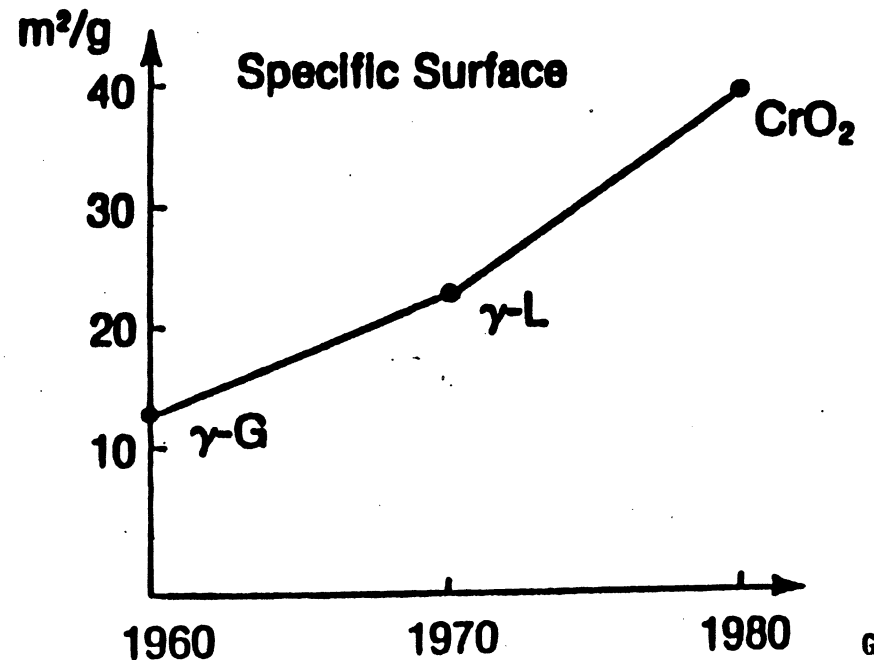
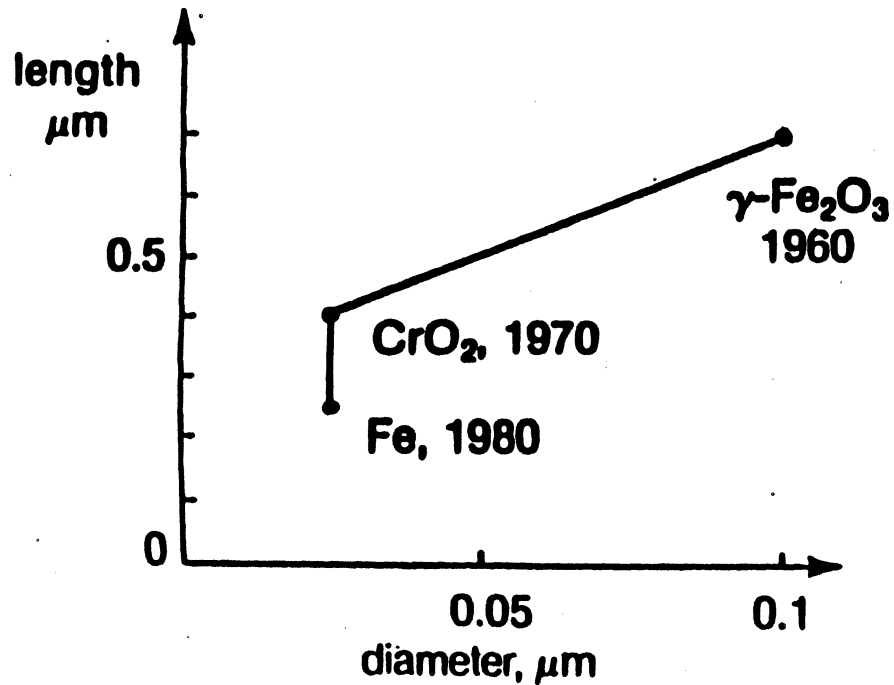
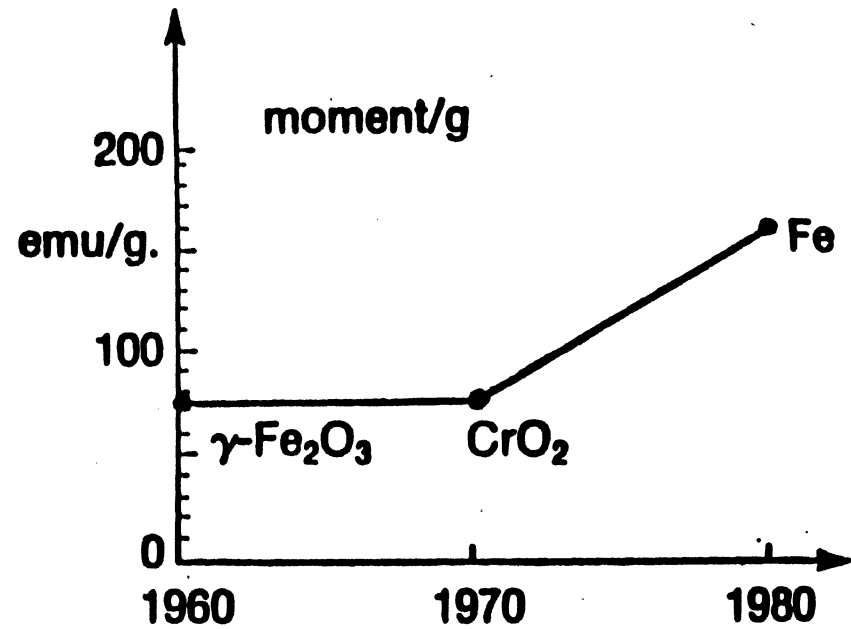
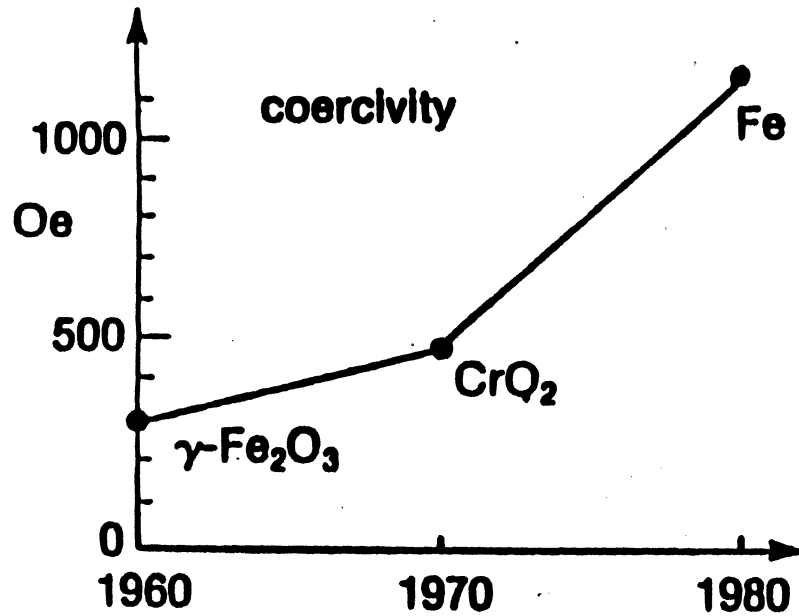


TABLE 3CONSUMPTION OF MAGNETIC PARTICLES BY APPLICATION

PARTICLE				1984		
	<u>1974</u>	<u>1977</u>	<u>1984</u>	<u>VIDEO</u>	<u>AUDIO</u>	<u>DATA</u>
IRON OXIDE	13	16	24	3%	65%	32%
COBALT-IRON OXIDE	-	0.5	15	90%	10%	-
CHROMIUM DIOXIDE	1	1.5	5	81%	12%	7%
METAL	-	-	-	-	100%	
	14	18	44			
	(millions of kilograms)					

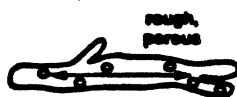
20
abandoned
of 1984

- NOTES: 1) FIGURES FOR 1974, 1977 FROM REF. 1
 2) FIGURES FOR 1984 FROM LENKE, PRESENTATION TO COMMITTEE
 3) AMOUNTS FOR METAL PARTICLES TOO SMALL TO LIST

MATERIALS FOR VERY HIGH DENSITY RECORDING

VHD PARTICLES

Conventional gamma-iron Oxide
(Co-impregnated)
Example: MDX particles



RECORDING MODE

Longitudinal

"Rice Grain" Gamma-iron Oxide
(Co-impregnated)



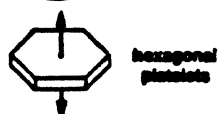
Longitudinal

Isotropic Gamma-iron Oxide
(Co-doped)



Longitudinal/Perpendicular

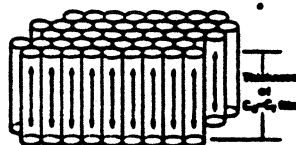
Barium Ferrite



Perpendicular

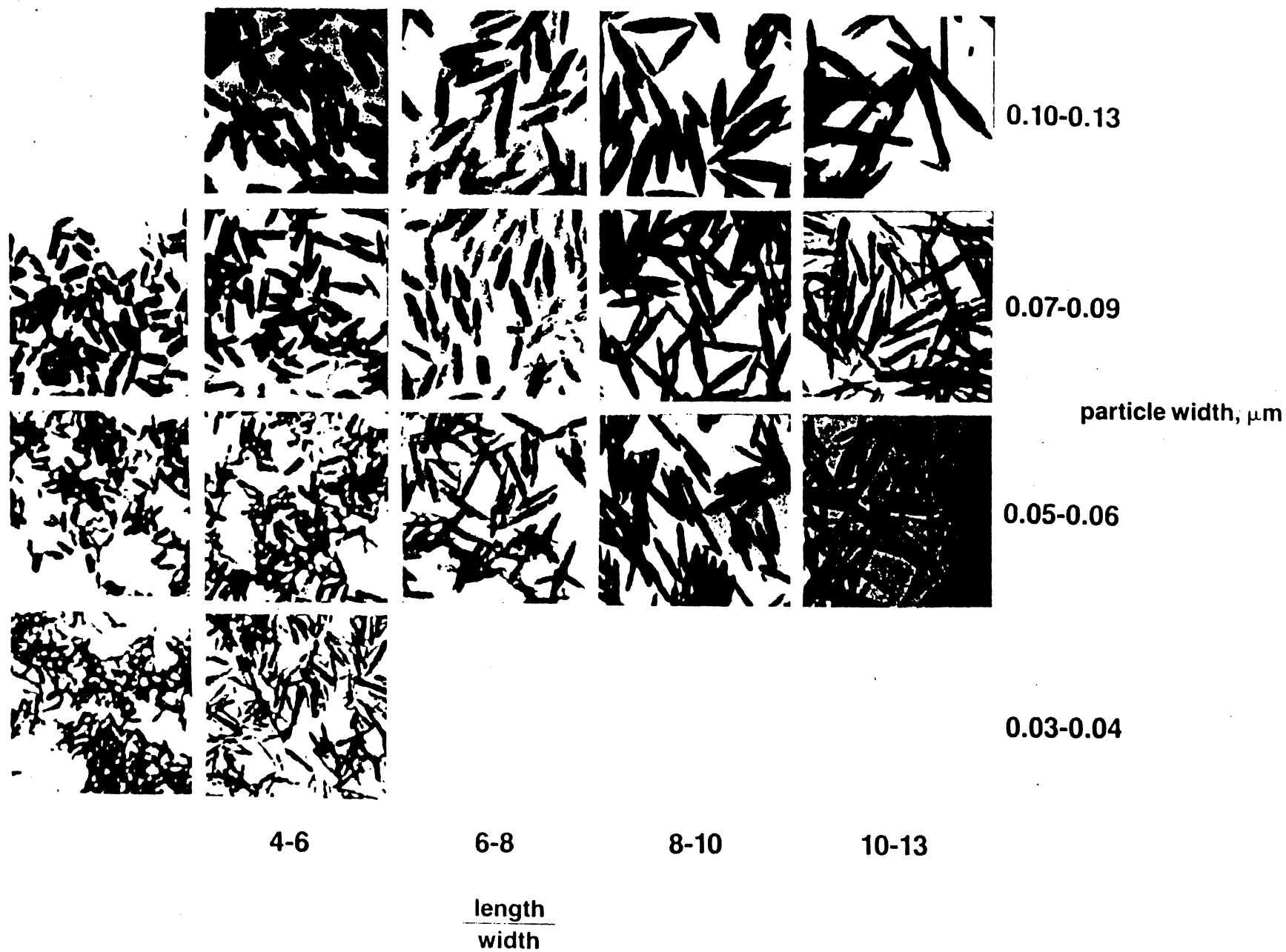
VHD THIN FILMS

Cobalt - Chrome
(sputtered)

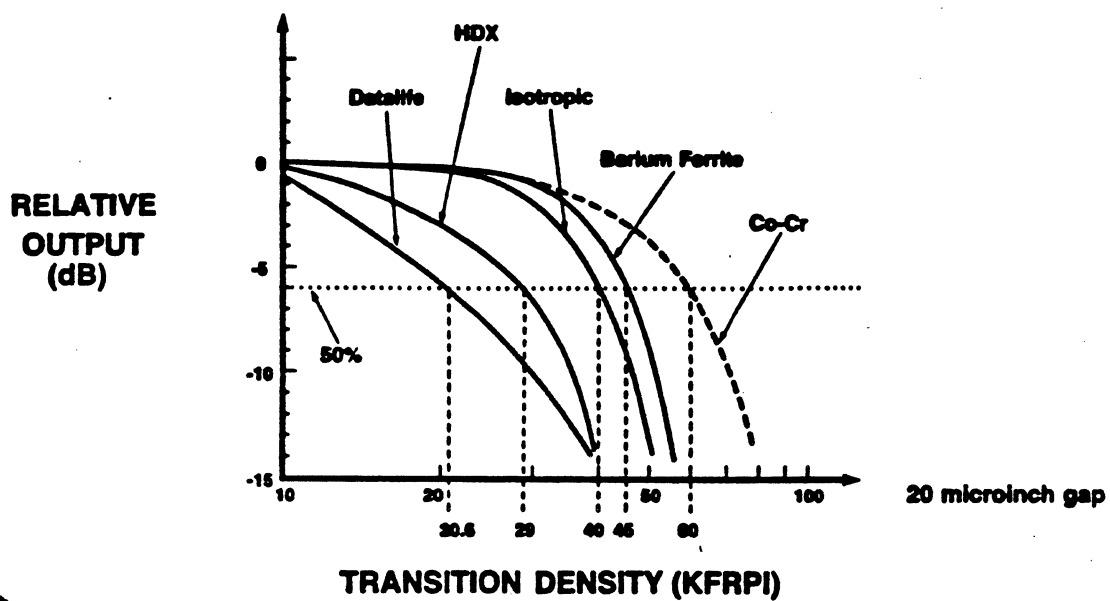


Perpendicular

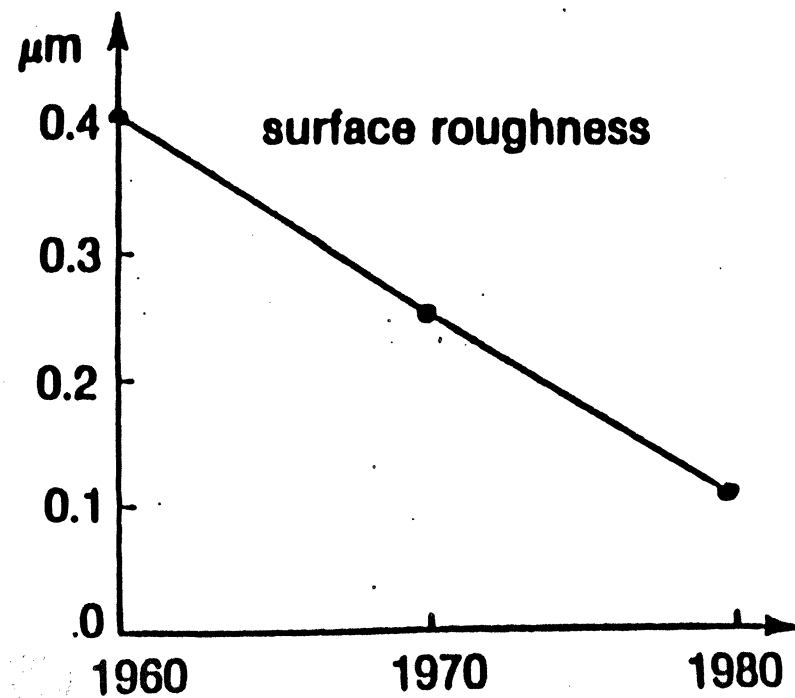
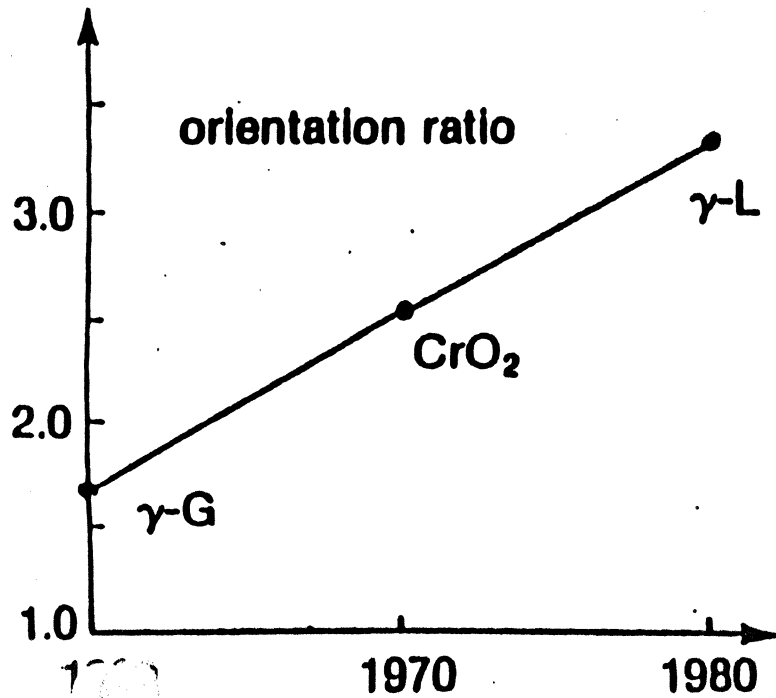
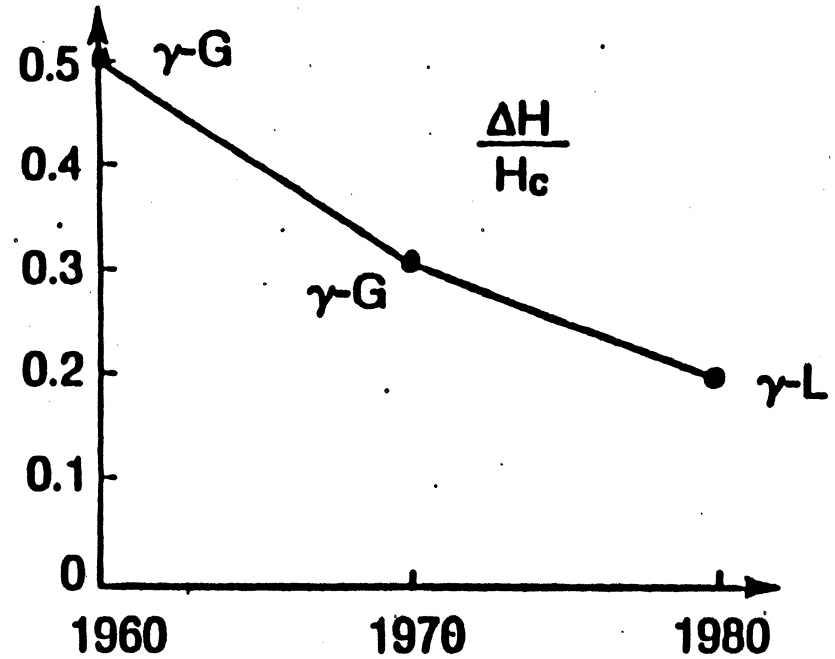
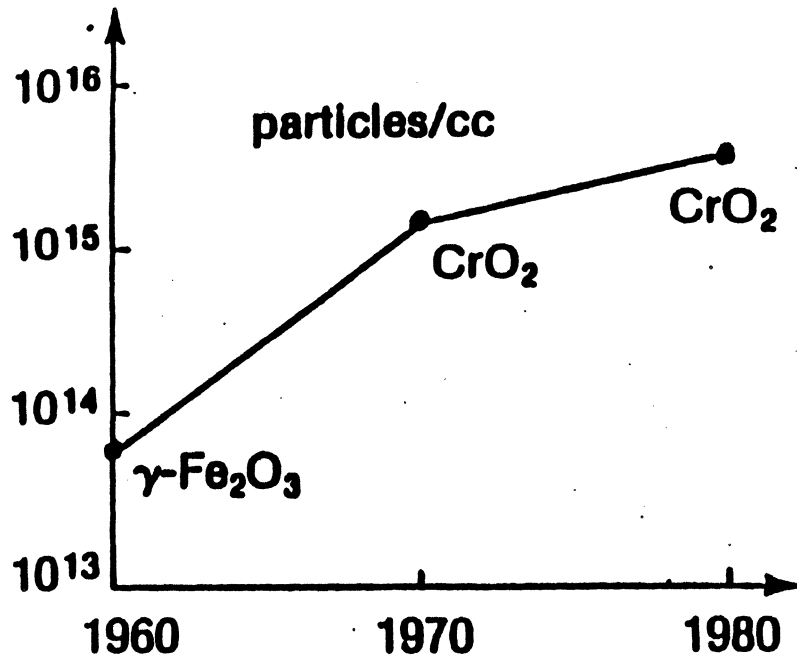
NP Particles

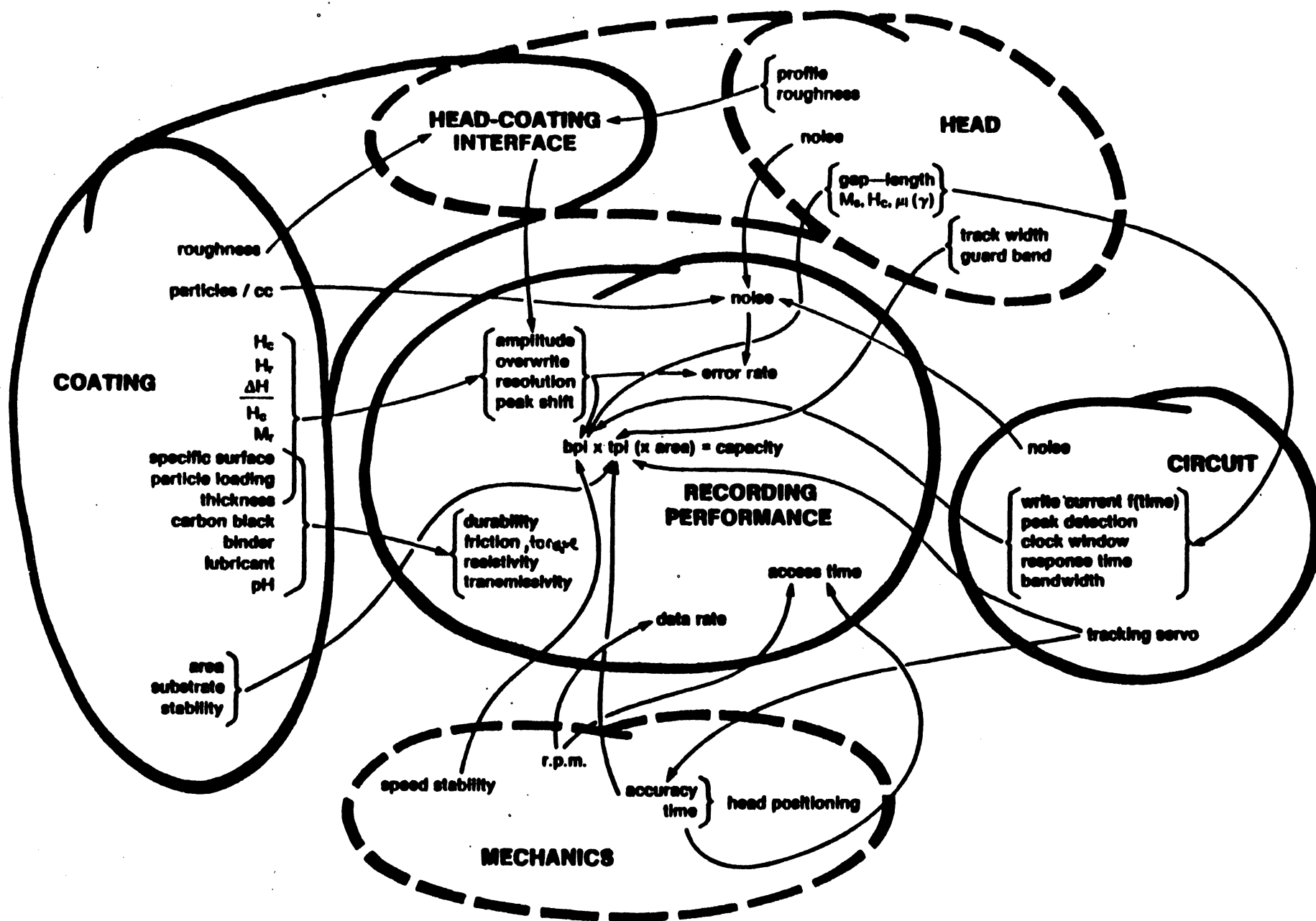


RELATIVE OUTPUT VS. TRANSITION DENSITY

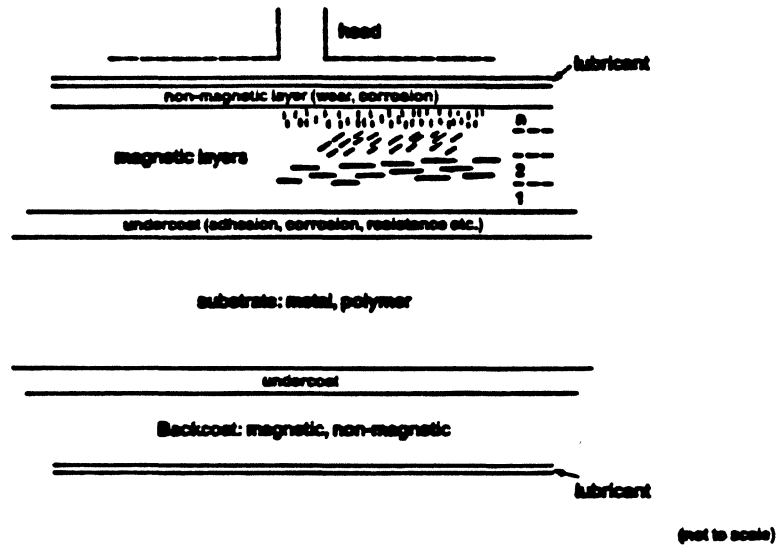


TAPE DEVELOPMENTS





Magnetic Recording Medium



THE DIAGRAM ILLUSTRATES A CROSS-SECTION OF A HYPOTHETICAL (AND UNUSUALLY COMPLEX) COATING.

MOST TAPES AND DISKS CONSISTS SIMPLY OF A SUBSTRATE AND ONE OR TWO MAGNETIC COATINGS.

PROBLEMS

Non-Uniformities:

examples; packing density of particles,
switching field of particles
bumps or holes on the surface.

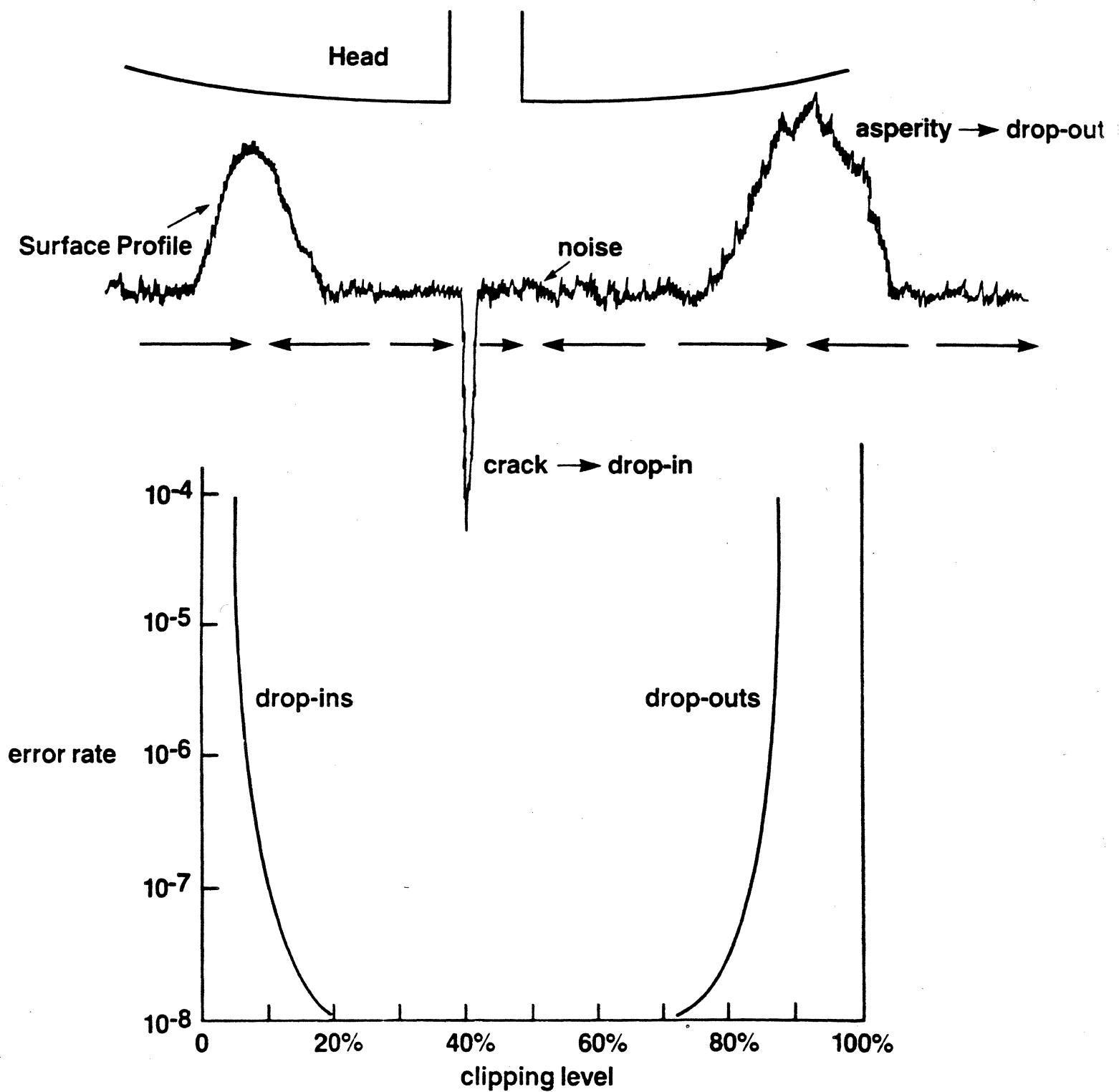
—small scale, $\leq \frac{\lambda}{2}$ —————→ noise, single-bit errors,
large $\frac{dMr}{dH}$, intersymbol interference,
overwrite and erasure problems.

—larger scale, $> \frac{\lambda}{2}$ —————→ burst errors

—still larger scale, $\gg \frac{\lambda}{2}$ —————→ poor uniformity of signal
with position in medium.

- "SINGLE-BIT ERRORS" ARE USUALLY ONLY FOUND ON RIGID DISKS.
- "BURST ERRORS" I.E. MULTIPLE-BIT ERRORS COMMONLY OCCUR IN TAPES AND FLEXIBLE DISKS.

Data Errors



PROBLEMS

Instabilities: of physical, chemical, mechanical properties with Time

Temperature
Humidity
Stress

examples:

- magnetic properties —————> print-through, signal fading
- head-track position —————> variations in signal level, errors
- mechanical, physical, chemical properties of coating —————> loss of lubricant,
wear failure,
corrosion,
tape stick,
scratch failure
- particle-binder interaction —————> change of magnetic properties,
corrosion,
cohesive strength
- market —————> product obsolescence

PROBLEMS

UNPREDICTABILITIES: from an imperfect understanding of materials interactions and processes

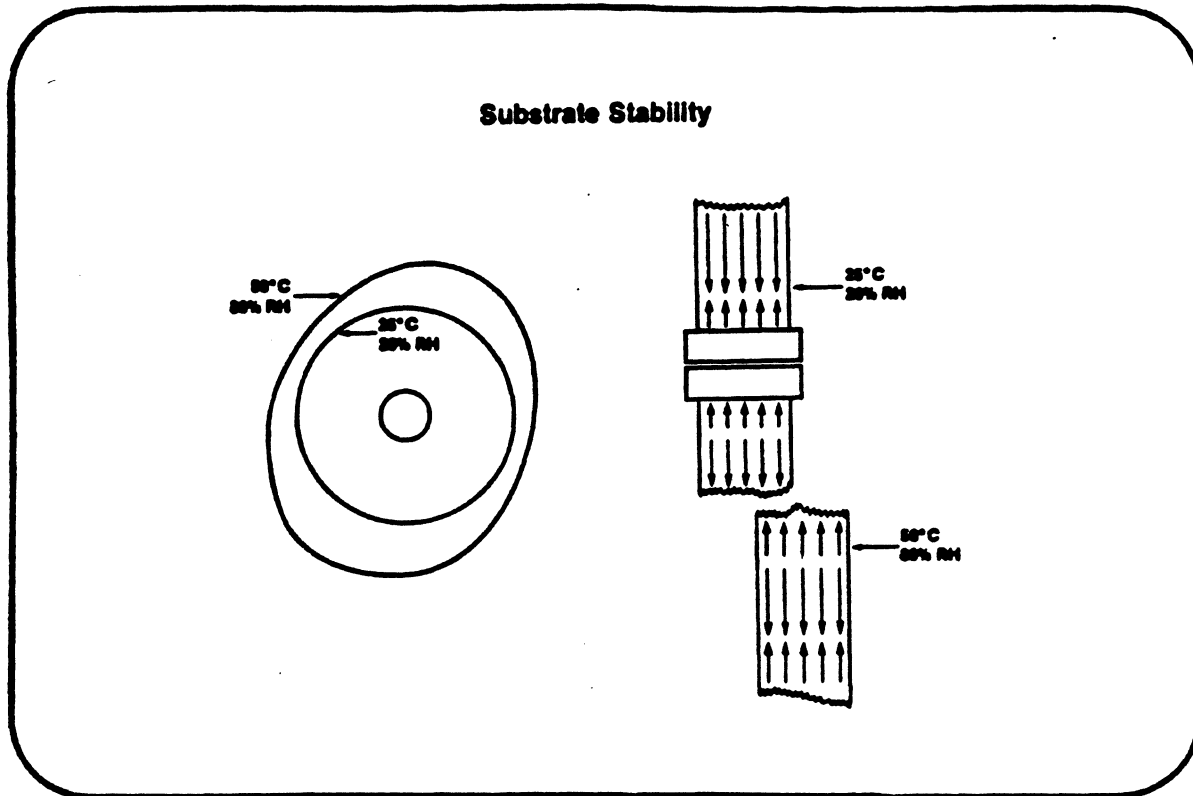
examples; —state of magnetization of an array of particles after a sequence of heads fields

—state of erasure

—magnetic properties of deposited films

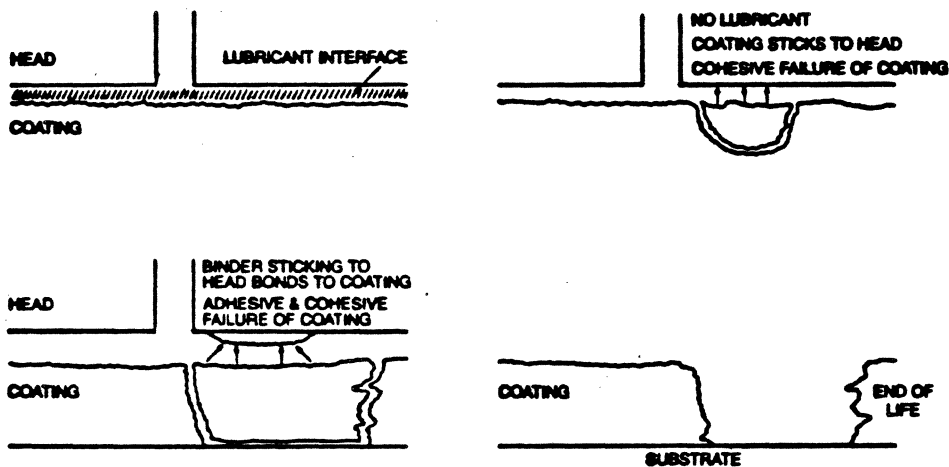
—effect of changing particles with similar magnetic properties

—improvement in recording performance for a given change in magnetic properties.



POLYETHYLENE TEREPHTHALATE IS USED AS THE SUBSTRATE IN FLEXIBLE DISKS. IT EXHIBITS ANISOTROPIC THERMAL AND HYGROSCOPIC COEFFICIENTS OF EXPANSION.

Flexible Disk: Failure Mechanism



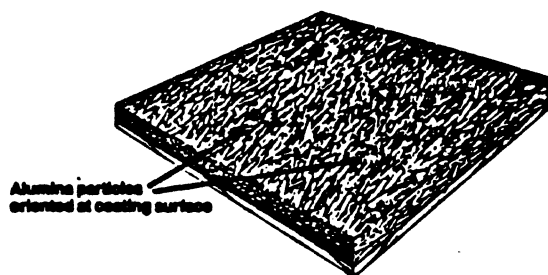
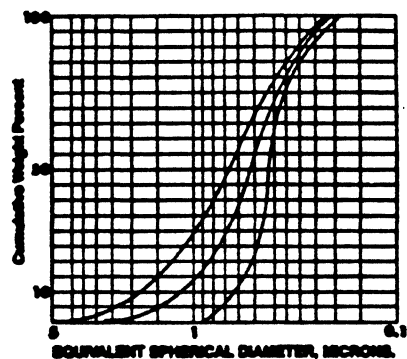
IN FLEXIBLE DISKS THE COMMON FAILURE MECHANISM IS NOT ABRASIVE WEAR BUT A COMBINATION OF THE COHESIVE FAILURE WITHIN THE COATING AND ADHESIVE FAILURE BETWEEN THE COATING AND THE SUBSTRATE.

THE ELAPSED TIME BETWEEN STEPS 1 AND 2 MAY BE MONTHS; THE TIME BETWEEN STEPS 2 AND 4 IS USUALLY MINUTES.

Alumina Additives

Characteristics

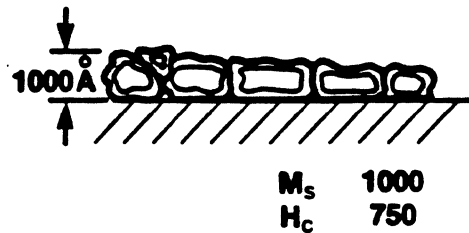
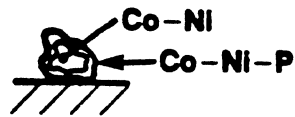
Crystal Form	— Monocrystalline Alpha Alumina
Specific Gravity	— 3.95 gm/cc
Hardness	— Knoop—2000, mohs—9
Surface Area	— 6–16 m ² /gm
pH	— 7.5–10
Moisture	— <0.25%
Average Particle Size	— 3–8 microns
Chemical Purity	— 99% + Al ₂ O ₃



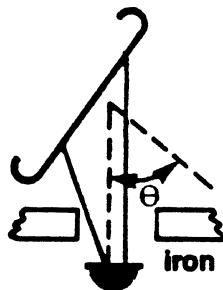
(Crows, Arvidson, 1963)

THIN FILMS

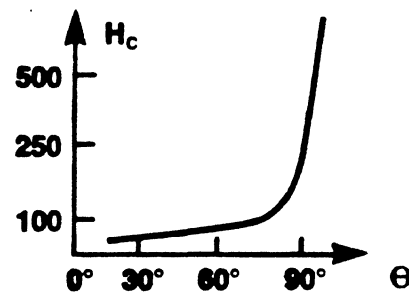
• Electroplating



• Vacuum Deposition



M_s 1600 H_c 750



• High coercivity thin films may be made by:

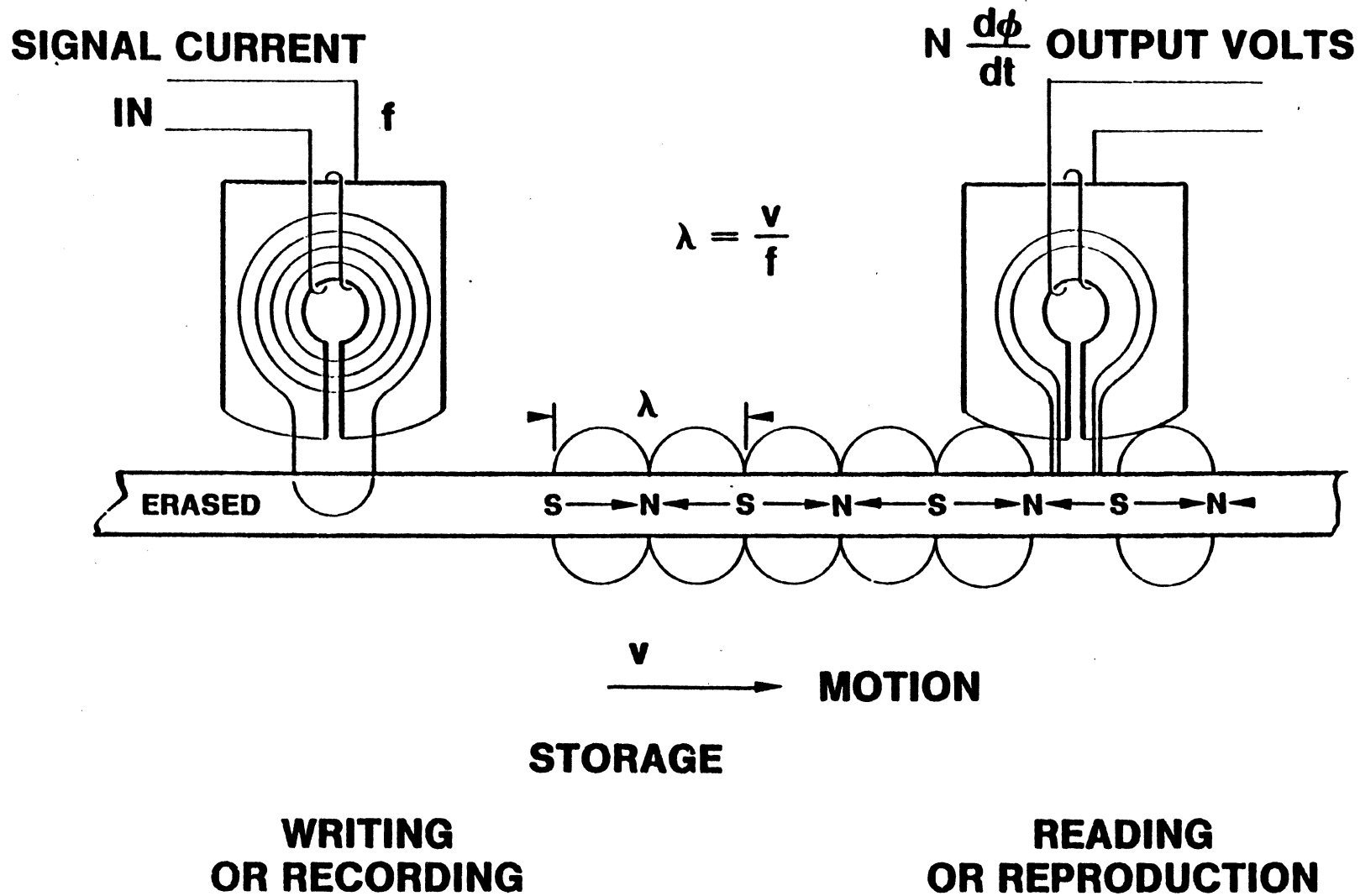
- electroplating
- chemical plating
- vacuum evaporation
- sputtering

• In every case, high H_c is only obtained if the film structure resembles an array of single-domain particles.

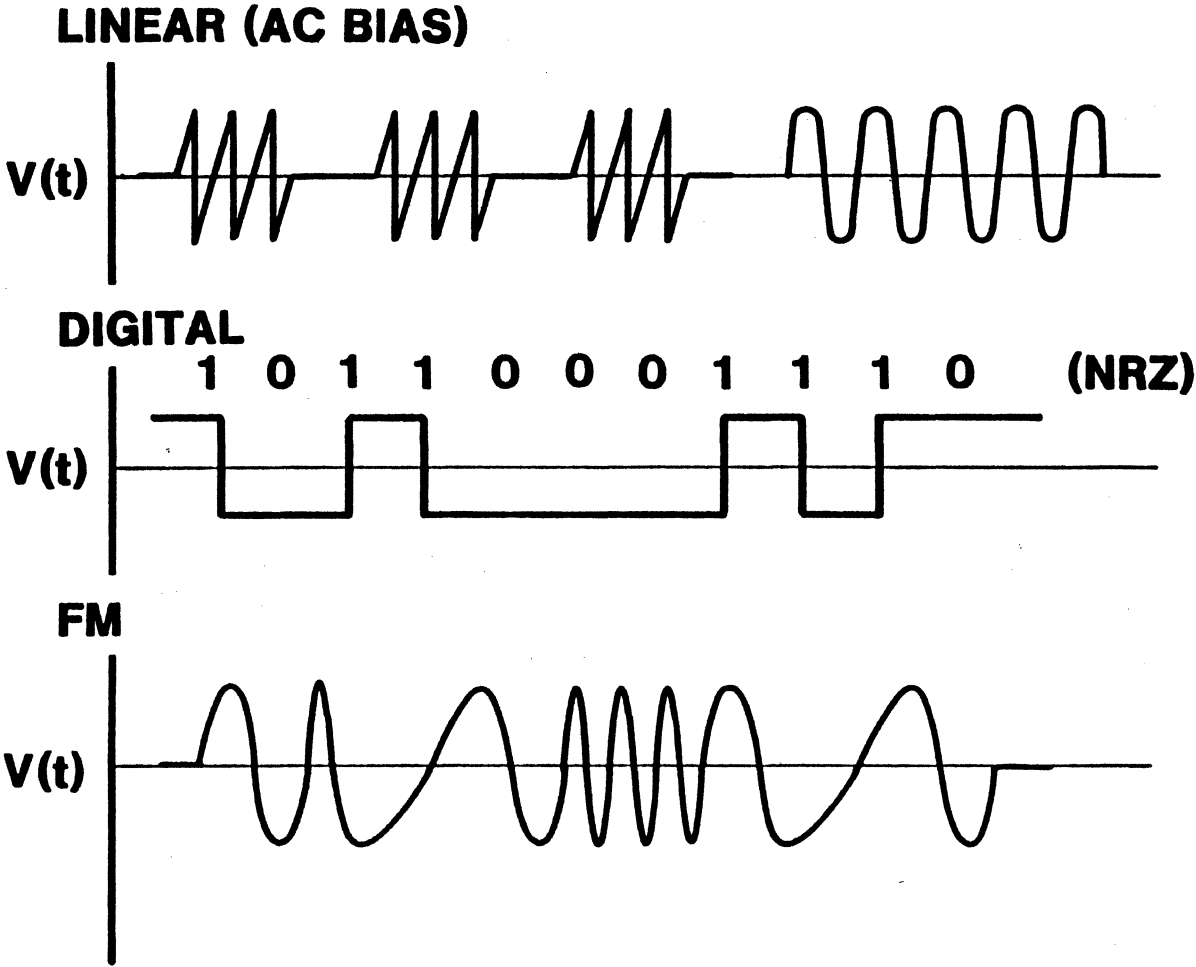
The Physics of Magnetic Recording

Neal Bertram, UCSD
Center for Magnetic Recording Research

FUNDAMENTAL PROCESSES



SIGNAL WAVEFORMS



RECORDING DENSITIES

HIGH DENSITY

RECORDER	SPEED	MAX f	MIN λ	SIGNAL
INSTRUMENTATION	1-120 ips	2 MHz	60 μ " (33 KBPI)	DIGITAL
QUAD VIDEO	1500 ips	15 MHz	100 μ "	F.M.
CONSUMER VIDEO	220 ips	7MHz	30 μ "	F.M.
AUDIO CASSETTE	1-7/8 ips	20 kHz	80 μ "	LINEAR
FUTURE COMPUTER DISC	1000 ips	10 MHz	100 μ " (20 KBPI)	DIGITAL

DEMAGNETIZATION FIELDS

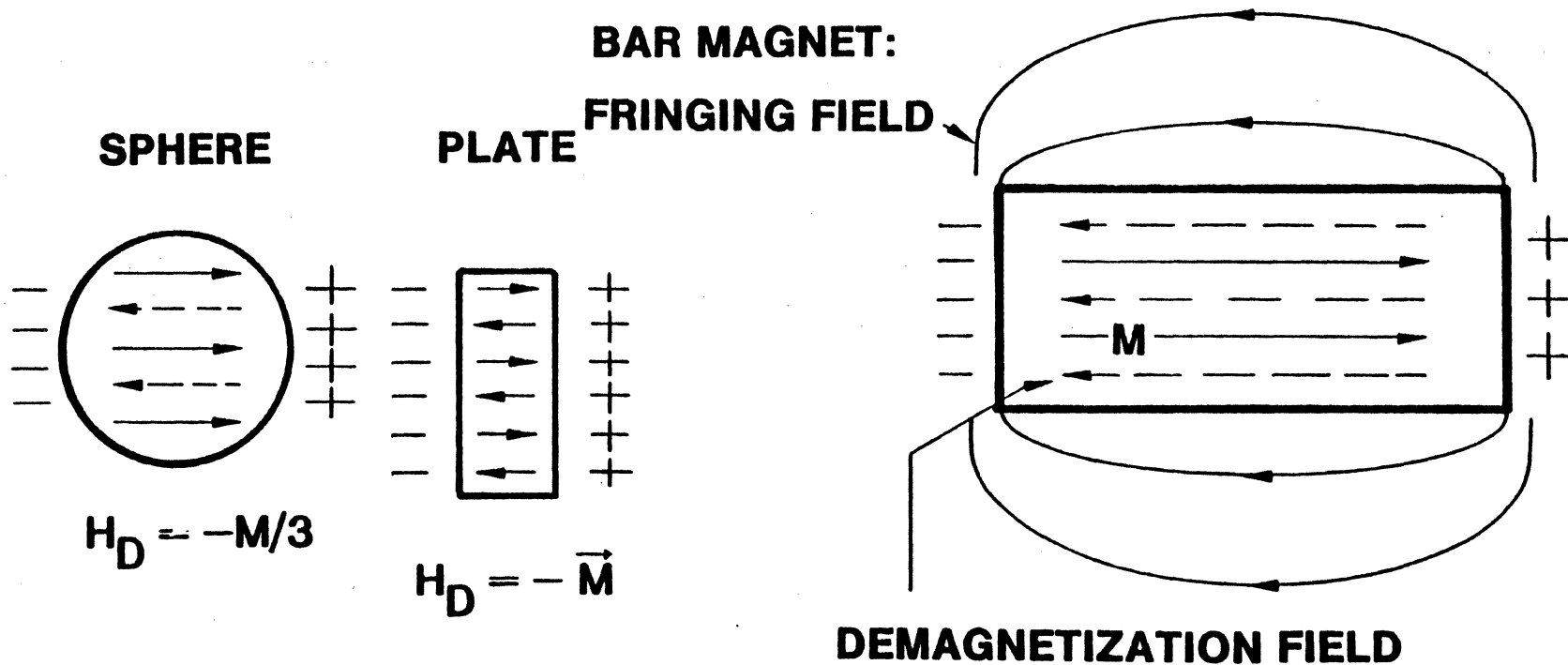
FOR CONTINUOUS MEDIA USE $\vec{H}$, $\vec{M}$

"FLUX DENSITY"

$$\vec{B} \equiv \mu_0 (H+M) \quad \vec{\nabla} \cdot \vec{B} = 0$$

$$\vec{\nabla} \cdot \vec{H} = - \vec{\nabla} \cdot \vec{M} \equiv \rho_M$$

ρ_M AS A "CHARGE DENSITY" IS A CONVENIENT WAY
TO DESCRIBE FIELDS FROM ELECTRONS IN A CONTINUUM



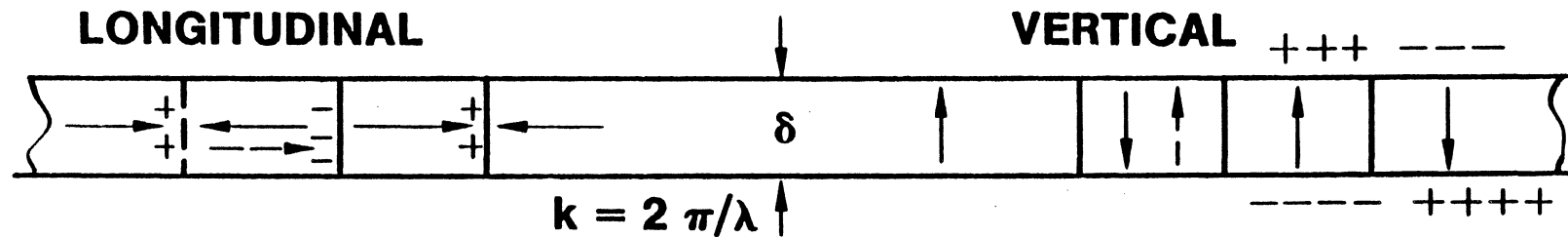
$$\mu = 4\pi \text{ in CGS}$$

$$\mu = 1 \text{ in MKS}$$

DEMAGNETIZATION FIELDS (Continued)

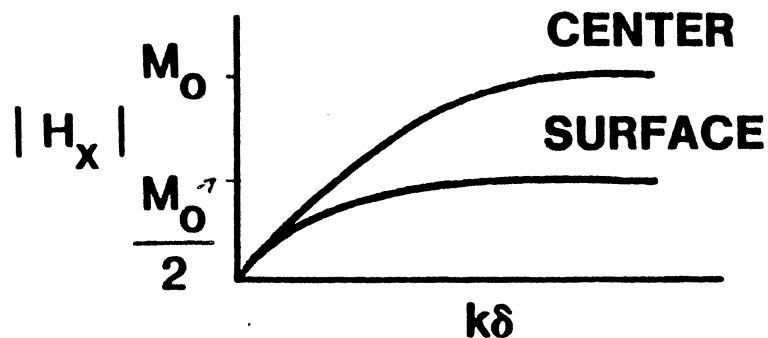
$$\vec{H}(\vec{r}) = -\frac{1}{4\pi} \int_{\text{VOLUME}} \frac{\vec{\nabla}' \cdot \vec{M}'(\vec{r} - \vec{r}') d^3 r'}{|\vec{r} - \vec{r}'|^3} + \frac{1}{4\pi} \int_{\text{SURFACE}} \frac{\vec{n}' \cdot \vec{M}'(\vec{r} - \vec{r}') d^2 r'}{|\vec{r} - \vec{r}'|^3}$$

EXAMPLES OF TAPE PATTERNS

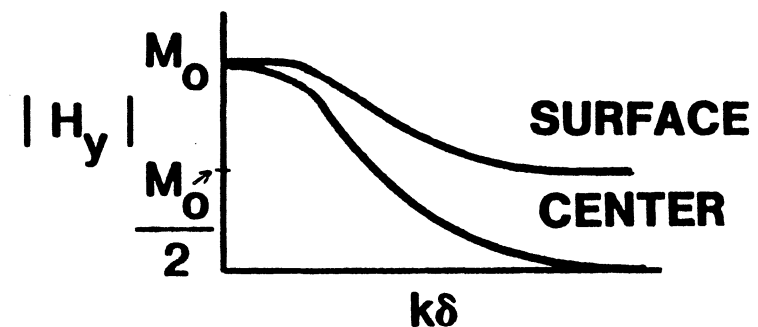


$$M = M_0 \sin kx$$

$$M = M_0 \sin kx$$



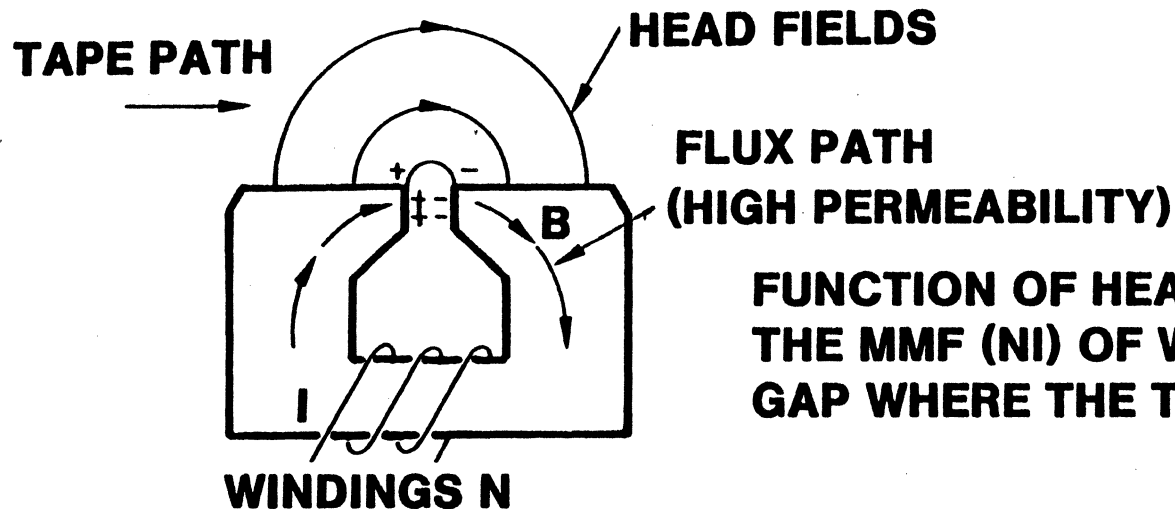
$$H_x^{\text{SURFACE}} = -\frac{M_0}{2} \left(1 - e^{-k\delta} \right) \sin kx$$



$$H_y^{\text{SURFACE}} = -\frac{M_0}{2} \left(1 + e^{-k\delta} \right) \sin kx$$

MAGNETIC HEADS

FUNDAMENTAL STRUCTURE



FUNCTION OF HEAD IS TO TRANSLATE
THE MMF (NI) OF WINDINGS TO THE
GAP WHERE THE TAPE PASSES

SIMPLEST APPROXIMATION (WIRE FIELD)

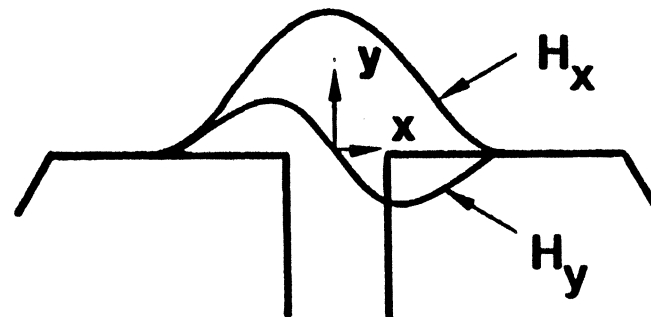
$$\oint H \cdot dl = NI \Rightarrow H = \frac{NI}{\pi r}$$

CONSTANT MAGNITUDE
FOR EACH RADII r

$$H_0 \equiv \text{DEEP GAP FIELD} \Rightarrow NI = H_0 g \text{ or } H_0 = \frac{NI}{g}$$

$$H_x = \frac{NIy}{\pi (x^2 + y^2)}$$

$$H_y = \frac{-NIx}{\pi (x^2 + y^2)}$$



HEAD FIELD EXPRESSION

I SOLVE POTENTIAL PROBLEM FOR FINITE PERMEABILITY μ

II FOR $\mu \rightarrow \infty$ AWAY FROM WIRES CAN SOLVE:

$$\nabla^2 \phi = 0, \vec{H} = -\vec{\nabla} \phi, \phi_s = \pm \frac{NI}{2}$$

ON OPPOSITE SURFACES

III KARLQUIST APPROXIMATION:

2 DIMENSIONAL, NO END AFFECTS, GIVES FIELD ABOVE HEAD TWO WAYS:

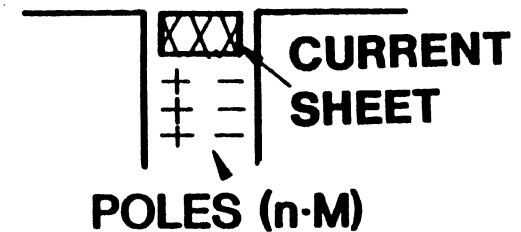
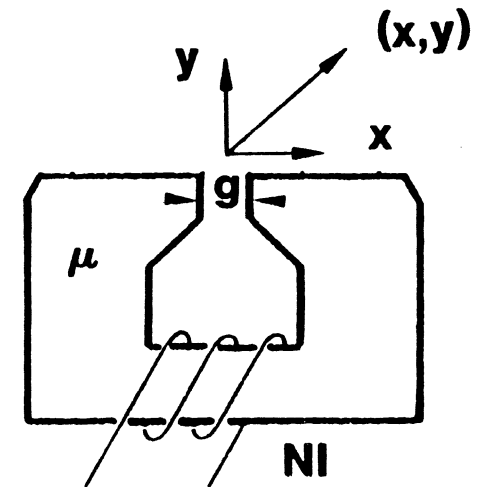
- 1) SOURCE SHEET OF CURRENT WIDTH g
- 2) UNIFORM POLES ON GAP FACE

RESULT

$$H_x = \frac{H_o}{\pi} \left\{ \tan^{-1} \frac{g/2+x}{y} + \tan^{-1} \frac{g/2-x}{y} \right\}$$

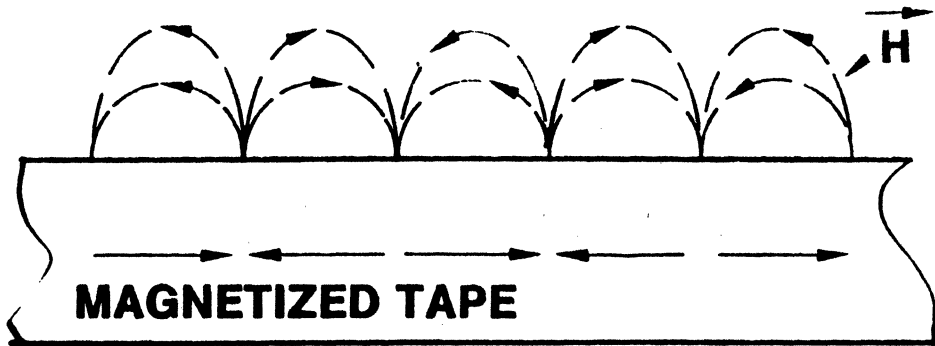
$$H_y = \frac{H_o}{2\pi} \ln \frac{(g/2-x)^2 + y^2}{(g/2+x)^2 + y^2}$$

$$H_o = \frac{NI\epsilon}{g} \quad \epsilon \equiv \text{EFFICIENCY}$$

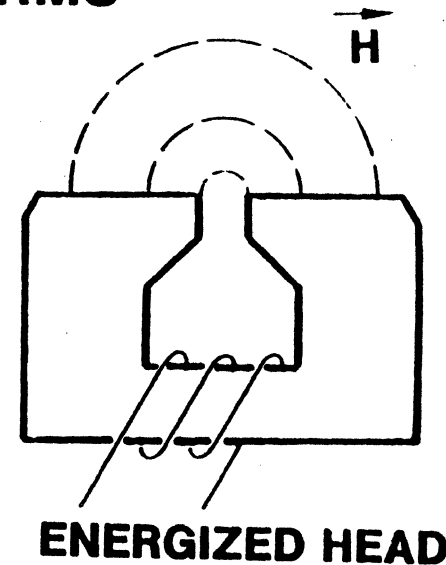


SOURCES

FIELD FOURIER TRANSFORMS



$\longleftrightarrow x$



$$f(k) \equiv \int_{-\infty}^{\infty} e^{-ikx} F(x) dx, \quad F(x) = \frac{1}{2\pi} \int_{-\infty}^{\infty} dk e^{ikx} f(k)$$

IN TWO DIMENSIONS:

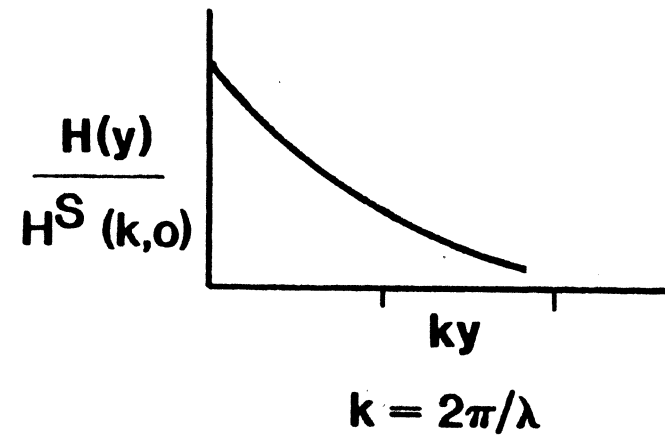
$$\nabla^2 \phi = \frac{\partial^2}{\partial x^2} \phi + \frac{\partial^2}{\partial y^2} \phi = 0$$

TRANSFORMING

$$-k^2 \phi(k, y) + \frac{\partial^2 \phi}{\partial y^2}(k, y) = 0$$

$$\phi(k, y) = \phi(k, 0) e^{-ky}$$

$$H_{x,y}(k, y) = H_{x,y}^S(k, 0) e^{-ky}$$

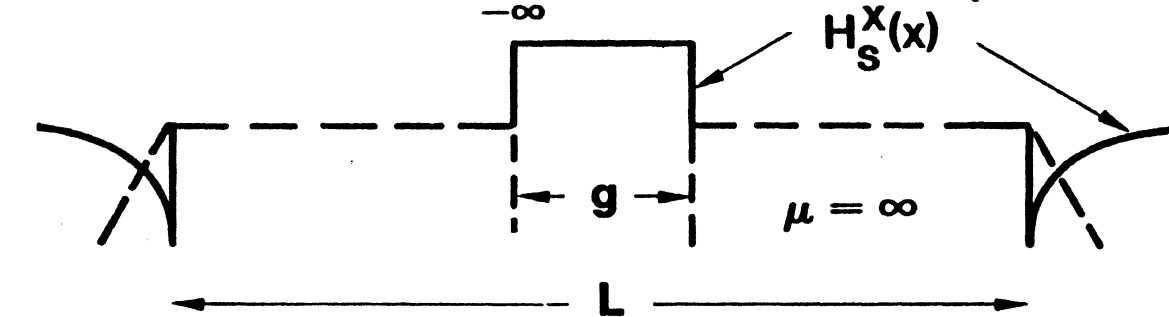


"SEE" EFFECTS TO $y \approx \lambda/3$

HEAD SURFACE EFFECTS

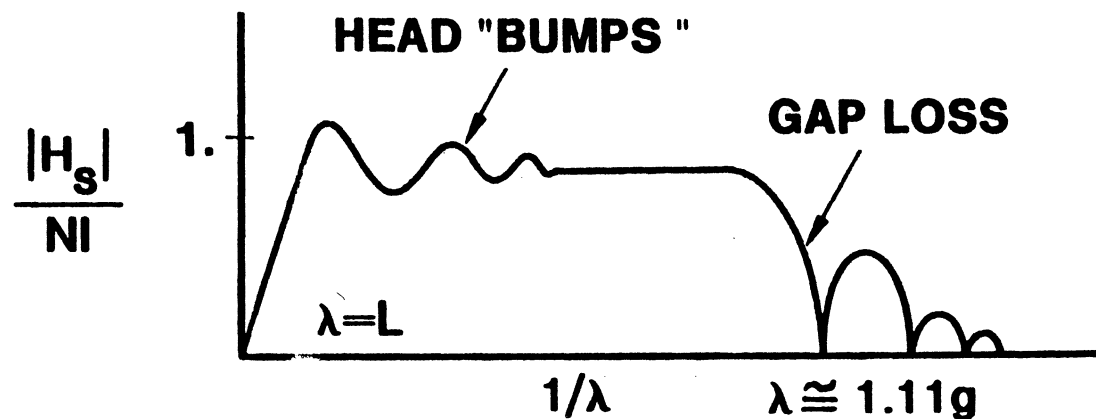
CAN SHOW (2D) $H_s^y(k) = iH_s^x(k)$ (ONLY A 90° ROTATION)

$$H_s^x(k) = \int_{-\infty}^{\infty} e^{-ikx} H_s^x(x) dx \quad (\text{VANISHES ON SURFACE})$$



$$\Rightarrow \frac{H_s^x(k)}{NI} \cong \frac{\sin 1.11 kg/2}{1.11kg/2} \cdot \text{EDGE EFFECTS (KL)}$$

$$H_s^x(k) \rightarrow 0 \text{ AS } k \rightarrow 0 \text{ SINCE } \int_{-\infty}^{\infty} H_s^x(x) dx = 0$$



REPRODUCE PROCESS

$$V = - \frac{Nd\phi}{dt} = - iN\epsilon\omega\phi_s \text{ (VOLTAGE)}$$

$$\omega = 2\pi f$$

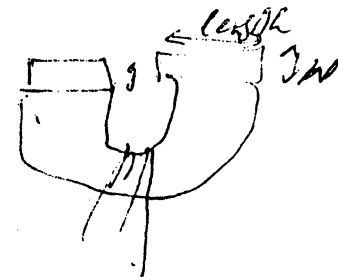
$$\phi_s = \frac{\mu_0 H_f W \lambda}{2\pi} \text{ (SURFACE FLUX)}$$

W. track width

length of the head = $\frac{\lambda}{2}$

$$\Rightarrow V = N \epsilon v W \mu_0 H_f$$

**VOLTAGE PER TURN PER TRACK WIDTH,
PER EFFICIENCY, PER SPEED IS EQUAL
TO SURFACE FRINGING FIELD!!**



UNITS:

(field at the head surface)

IF H_f IN Oe

$$V / N \epsilon v W \text{ (nV/TURN-MIL-IPS-EFF)} = H_f / 16$$

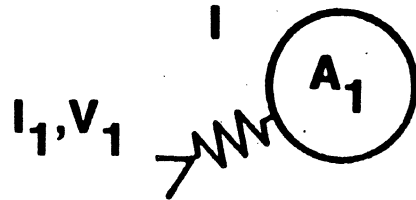
$$V = 62.5 \mu V \text{ FOR } H_f = 200$$

$$N = 10, \epsilon = .5, W = 1 \text{ MIL}$$

$$v = 1000 \text{ IPS}$$

RECIPROCITY

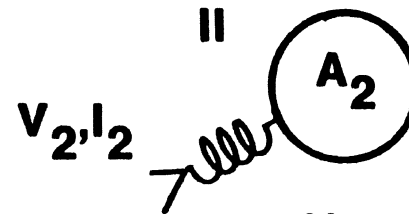
EQUIVALENCE OF MUTUAL INDUCTANCE FOR TWO SOURCES



FOR CURRENT IN I (I_1)

$$\phi_2 = \int_{A_2} d\mathbf{a} \cdot \mathbf{H}_{21}$$

H_{21} is FIELD DUE TO I_1
EVALUATED AT A_2



FOR CURRENT IN II (I_2)

$$\phi_1 = \int_{A_1} d\mathbf{a} \cdot \mathbf{H}_{12}$$

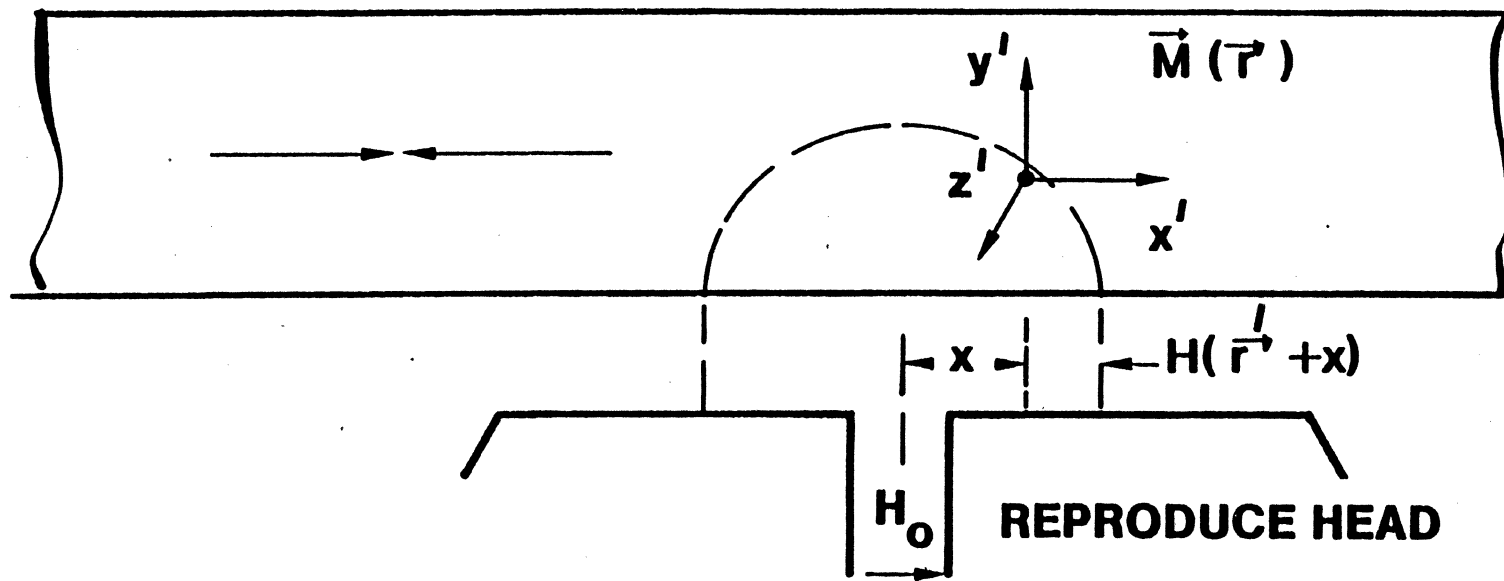
CONVERSE FOR H_{12}

$$\frac{\phi_2}{I_1} = \frac{\phi_1}{I_2} \Rightarrow \phi_2 = \frac{\phi_1 I_1}{I_2} = \int_{A_1} \frac{d\mathbf{a} I_1 \cdot \mathbf{H}_{12}}{I_2}$$

**I CAN BE MAGNETIZED TAPE SINCE CURRENT
LOOPS CAN BE EQUIVALENT (EXTERNALLY)
TO MAGNETIC DIPOLES**

II CAN BE REPRODUCE HEAD

RECIPROCITY (Continued) $\rightarrow v \ (x = vt)$

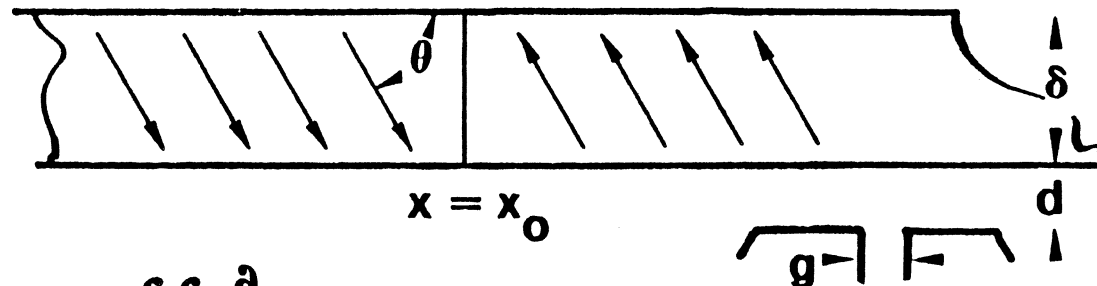


REPRODUCE FLUX EXPRESSED AS:

$$\phi_{\bullet}(x) = \mu_0 \iiint_{\text{TAPE}} \vec{M}(\vec{r}') \cdot \vec{H}(\vec{r}' + x) d^3r'$$

- 1) H IS EVALUATED WITH UNIT NI APPLIED TO HEAD
- 2) RECIPROCITY IS A CORRELATION OF M & H

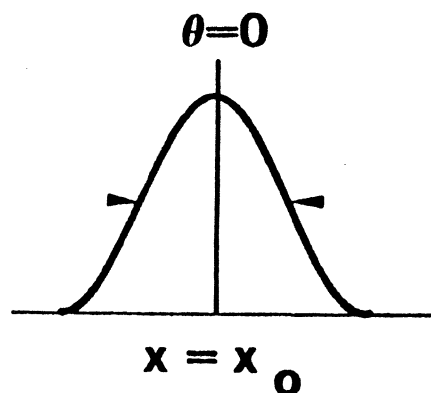
REPRODUCTION OF SINGLE PERFECT TRANSITION



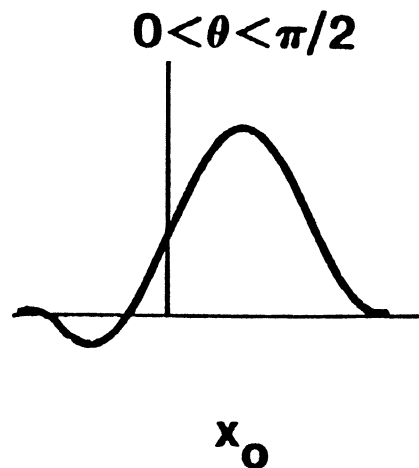
$$\frac{V}{N\epsilon W_V} = \mu_0 \iint \frac{\partial}{\partial x'} M(x') \cdot H(r'+x) dx' dy'$$

FOR THIN MEDIA

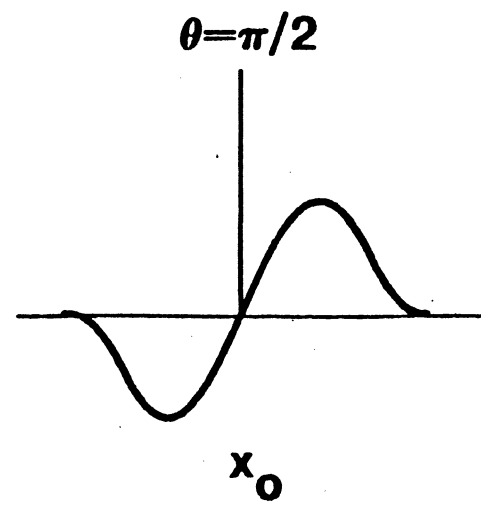
$$\frac{V(x)}{vN\epsilon W} = 2\mu_0 M_0 \delta \left\{ H_x(x_0+x, d+\delta/2) \cos\theta - H_y(x_0+x, d+\delta/2) \sin\theta \right\}$$



LONGITUDINAL M



INTERMEDIATE



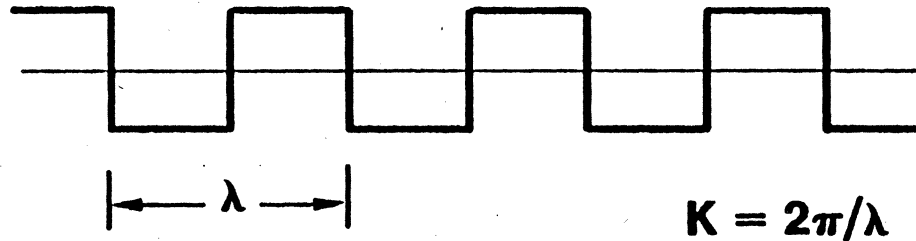
VERTICAL M

$$PW_{50} = \sqrt{g^2 + 4d(d+\delta)}$$

SPECTRAL RESPONSE

**SQUARE WAVE
RECORDED**

$M(x)$



RMS FUNDAMENTAL VOLTAGE

$$V_{rms} = .707 \frac{2}{\pi} K V_{pulse}(K)$$

$$\frac{V_{pulse}(k)}{NW_{\epsilon V}} = \mu_0 \int_d^{d+\delta} dy' k M_k(y') \cdot H_s(k) e^{-ky'}$$

1/3 wave length = 1/3 period (2wavelength)

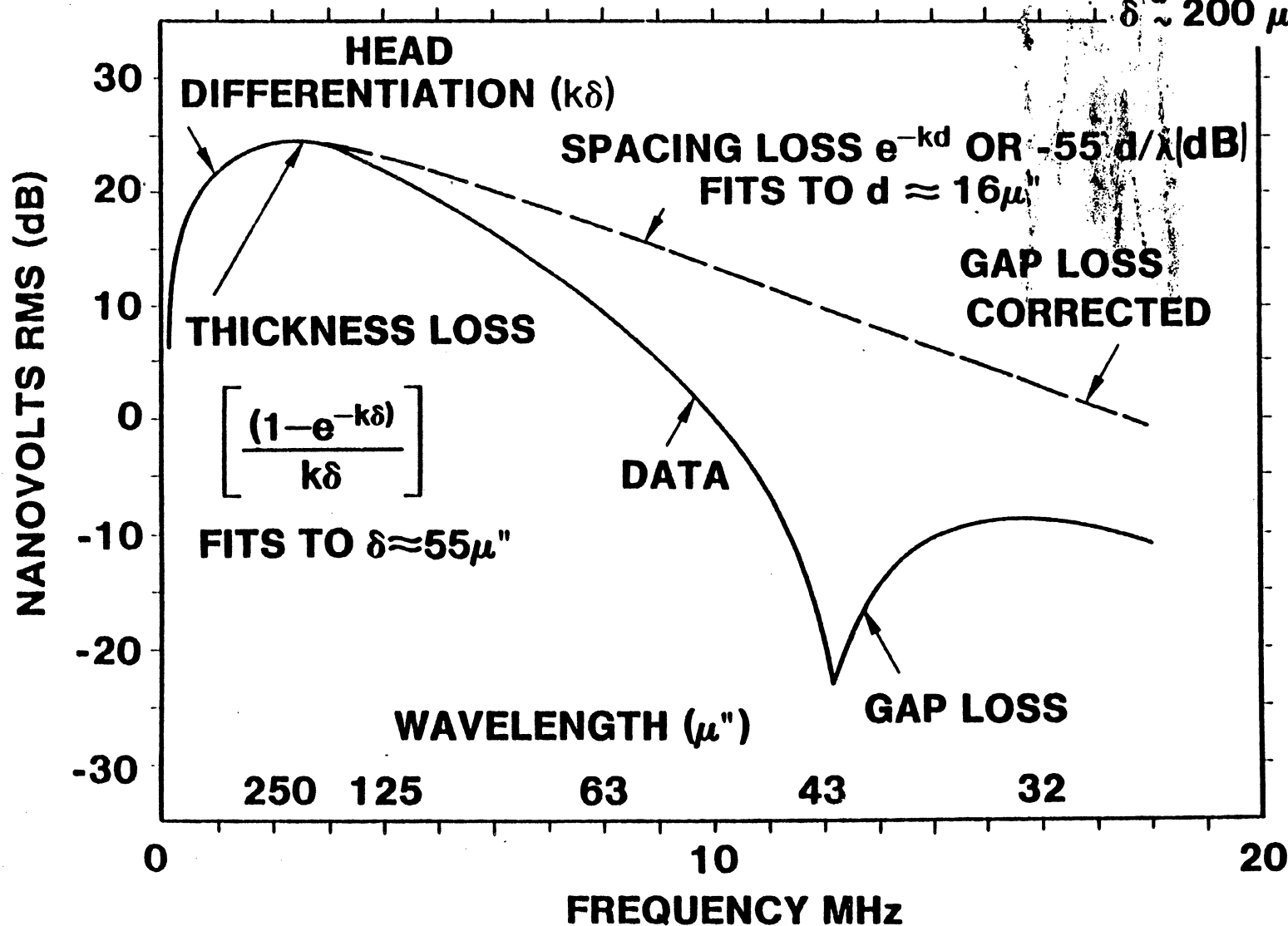
$$\frac{V_{rms}}{NW_{\epsilon V}} = .707 \times \frac{4}{\pi} \times \mu_0 M_0 K \delta \frac{(1 - e^{-k\delta})}{k\delta} e^{-kd} \frac{\sin 1.11kg/2}{1.11kg/2}$$

MAGNETIZATION LEVEL (points to $\mu_0 M_0$)
HEAD DIFFERENTIATION (points to K)
THICKNESS LOSS (points to $k\delta$)
SPACING LOSS (points to e^{-kd})
GAP LOSS (points to $\frac{\sin 1.11kg/2}{1.11kg/2}$)

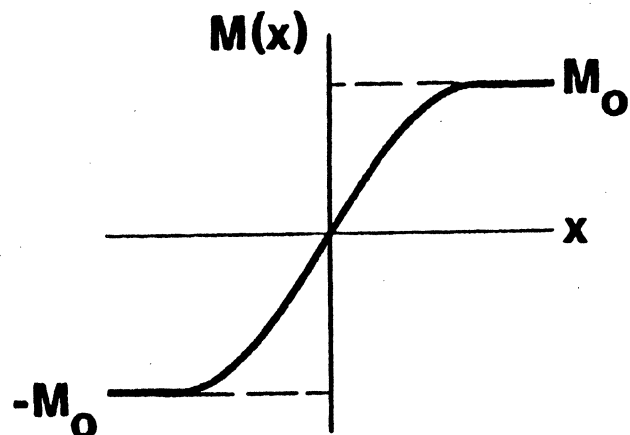
EXPERIMENTAL SPECTRAL CURVE

$v = 500$ IPS
OPTIMIZATION @
 $60 \mu''$ WAVELENGTH

TAPE: '196'
 $M_r \sim 1200$ G
 $H_c \sim 700$ Oe
 $\delta \sim 200 \mu''$



FINITE TRANSITION LENGTH



ARCTANGENT APPROXIMATION:

$$M(x) = \frac{2}{\pi} M_0 \tan^{-1} x/a$$

TRANSFORM:

$$M(k) = 2iM_0 e^{-ka}/k$$

ASSUME a INCREASES LINEARLY INTO MEDIUM

$$a(y) = a_s + \alpha(y-d)$$

$$d < y < d + \delta \quad \alpha = (a_b - a_s)/\delta$$

EFFECT ON PULSE OR SPECTRA

$$d \rightarrow d + a_s,$$

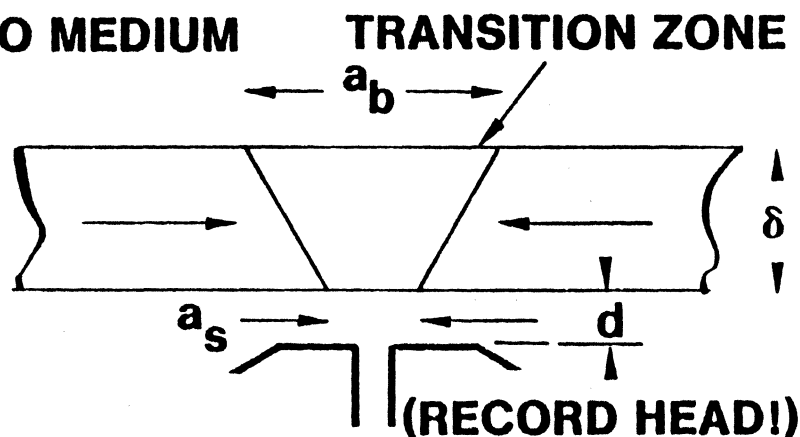
$$\delta \rightarrow \delta^* = \delta + a_b - a_s$$

$$V \text{ OR } \phi \rightarrow V \text{ OR } \phi / (1 + \alpha)$$

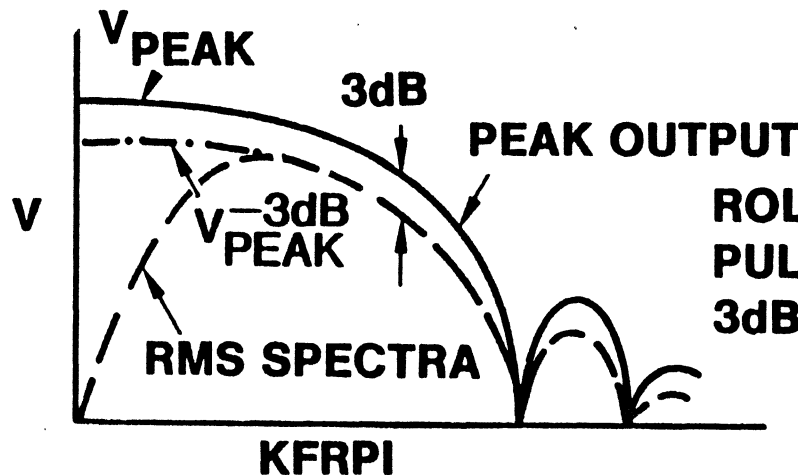
PW₅₀

(LONG)

$$= \sqrt{g^2 + 4(d+a_s)(d+a_s+\delta^*)} = \sqrt{g^2 + 4(d+a_s)(d+a_b+\delta)}$$



"ROLL-OFF" CURVE



ROLL-OFF CURVE JOINS SPECTRA WHEN PULSES BEGIN TO OVERLAP (EXCEPT FOR 3dB PEAK TO RMS SHIFT)

D_{50} IS DEFINED BY DENSITY WHERE PEAK OUTPUT DROPS 50%

SIMPLE FORM: FROM PULSE EQUATIONS FOR THIN MEDIA ($\alpha = 0$)

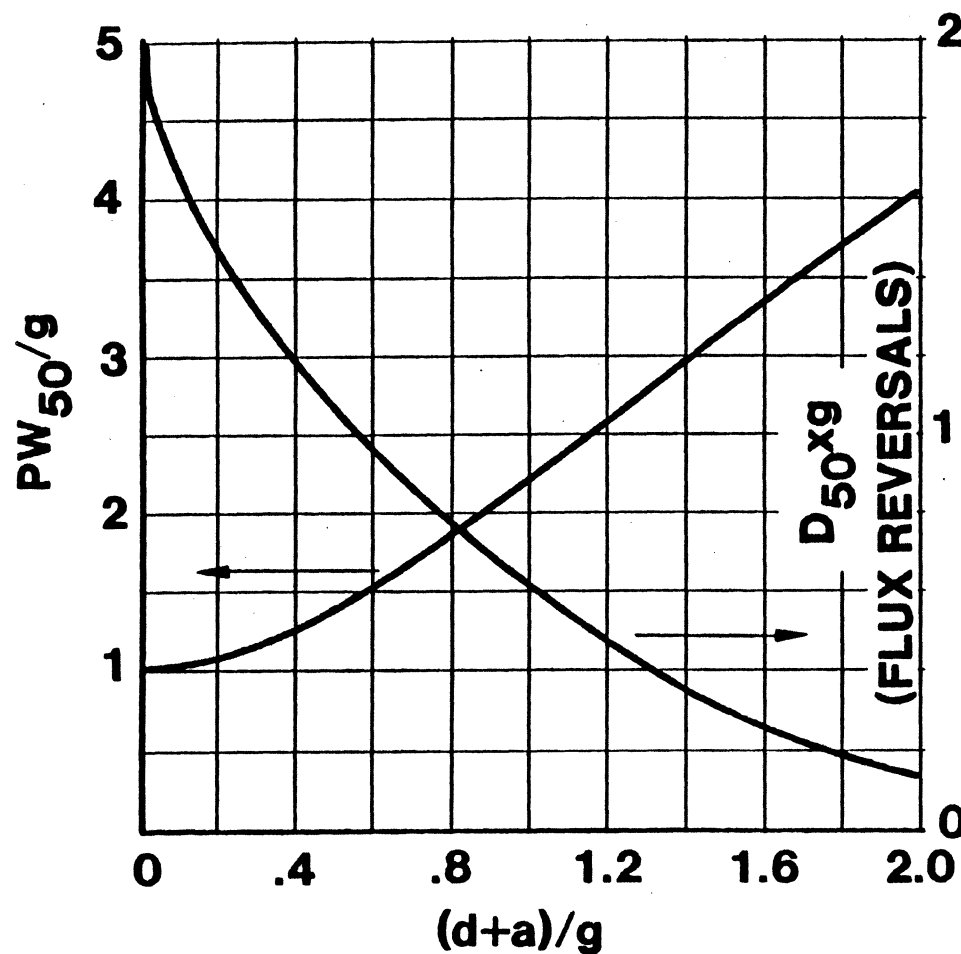
$$V_{\text{PEAK}} = \frac{4}{\pi} M_0 \tan^{-1} \frac{g}{2(d+a)}$$

$$V_{\text{rms}} = \frac{1}{\sqrt{2}} \frac{4}{\pi} M_0 k \delta e^{-k(d+a)} \frac{\sin kg/2}{kg/2}$$

D_{50} OCCURS FOR THAT k WHERE

$$\frac{V_{\text{peak}}}{\sqrt{2}} = 2V_{\text{rms}}$$

APPROXIMATE D_{50} CURVE



EXAMPLES $g = 27 \mu''$
 $d = 10 \mu''$

DISK	PW_{50}	D_{50}
H_c 450 Oe δ $3 \mu''$ M_r 10,000 G a_{th} $22 \mu''$	67.5 μ''	20 KFRPI
H_c 900 Oe δ $1.1 \mu''$ M_r 10,000 G a_{th} $5 \mu''$	40.5 μ''	35 KFRPI

APPLIES TO LONGITUDINAL RECORDING

$D_{50} \times g$ IS FLUX REVERSALS PER INCH TIMES INCH

OR FLUX REVERSALS PER METER TIMES METER

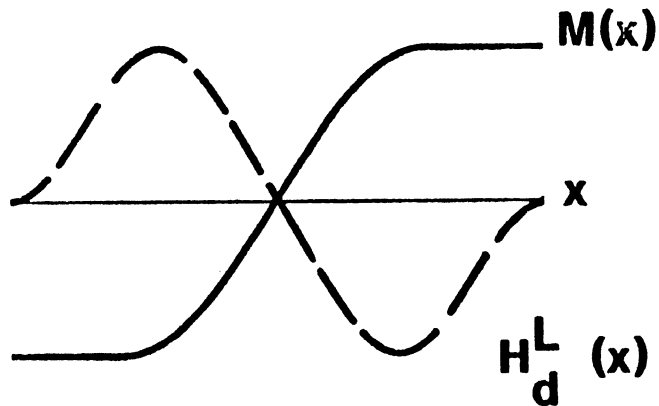
RECORD PROCESS

ULTIMATE DEMAGNETIZATION UNIT:

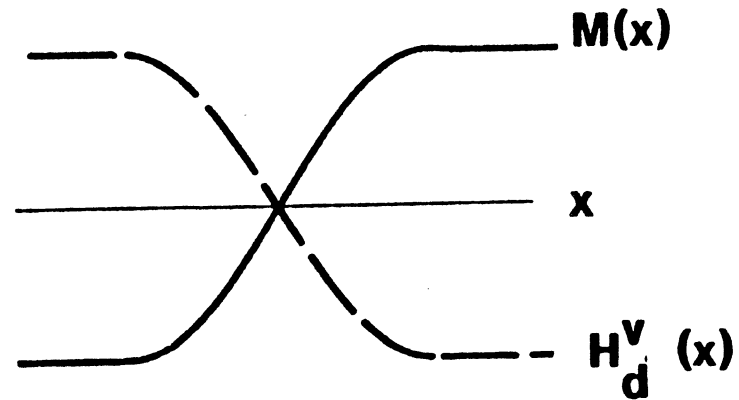
$$H_{\text{demag}} \leq H_c$$

ISOLATED TRANSITION

LONGITUDINAL



VERTICAL

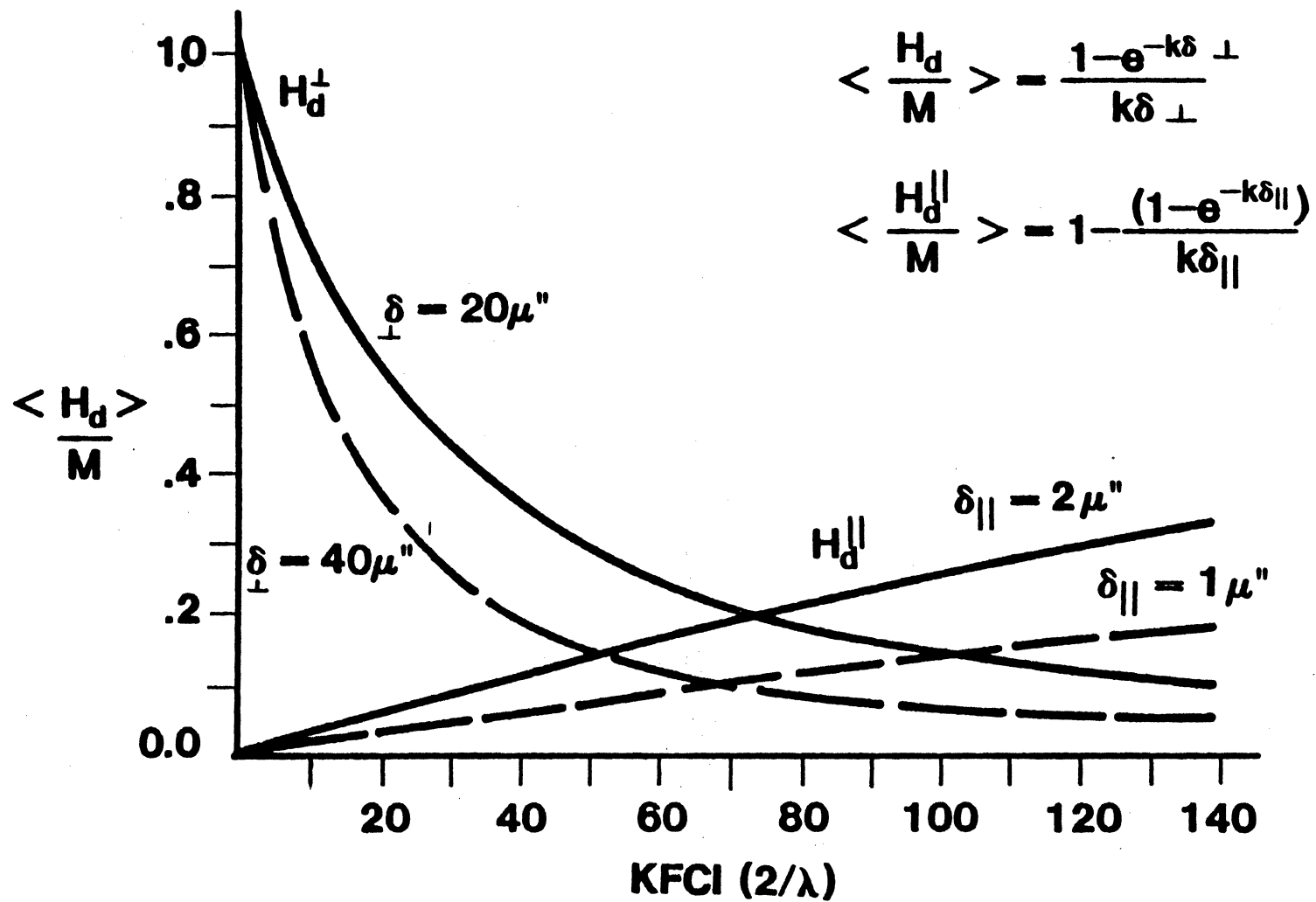


OVERLAPPING TRANSITIONS (SINEWAVE):

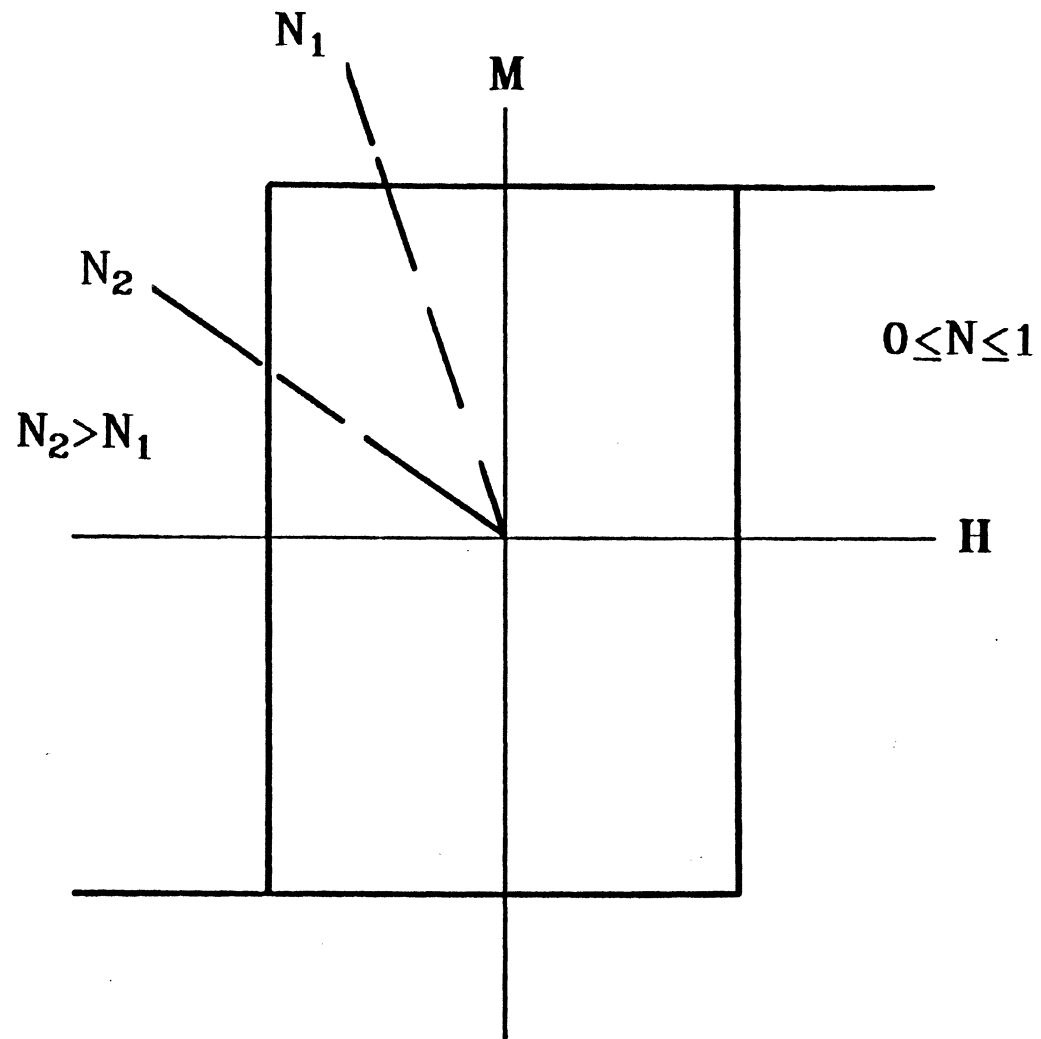
$$H_d (\text{SURFACE}) = M/2 \leq H_c \text{ (BOTH L \& V)}$$

RECORD PROCESS DOES NOT PERMIT THIS
LIMIT TO OCCUR!!

AVERAGE DEMAGNETIZATION FIELD



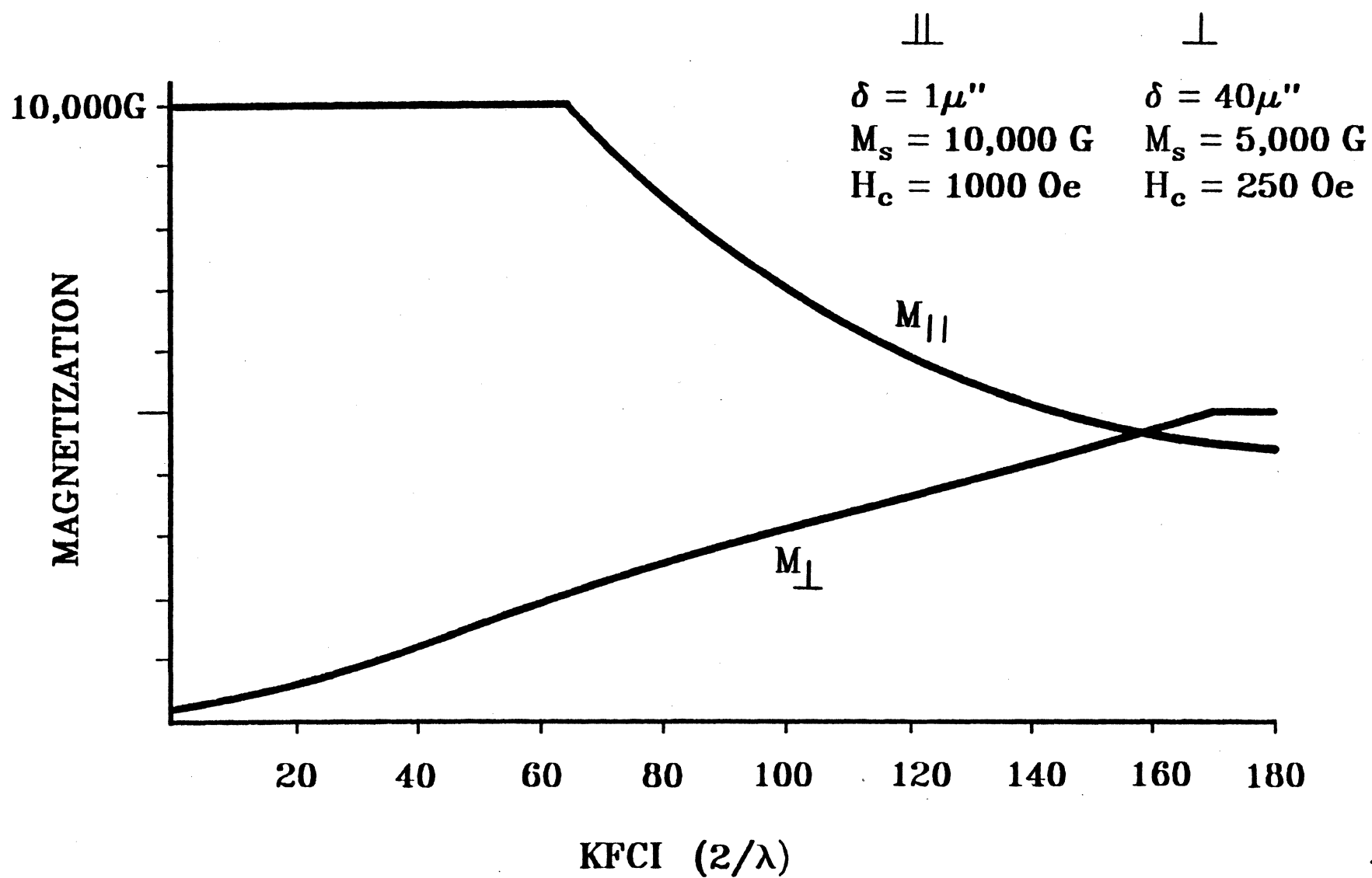
LOOP SCLARING



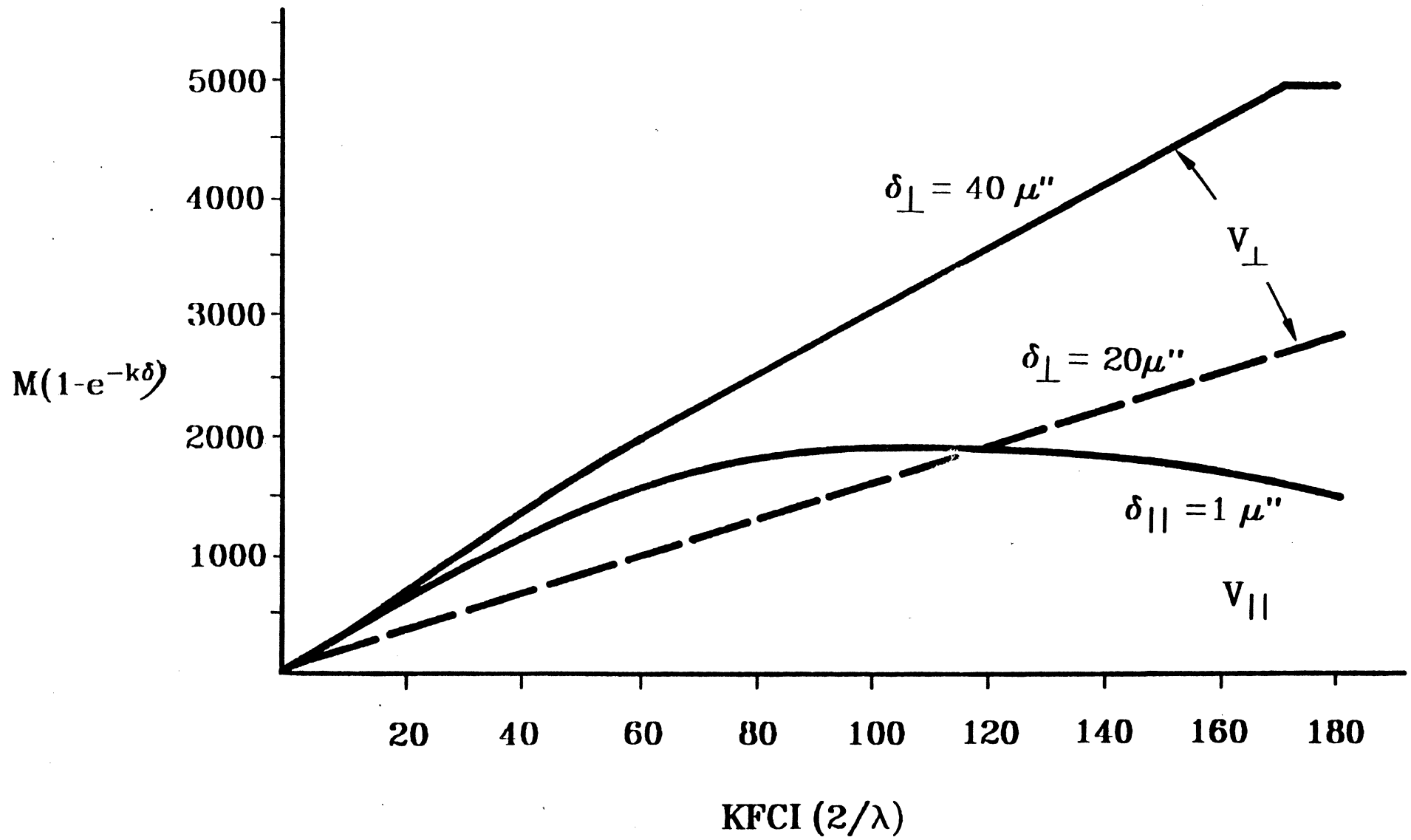
$$H_d = -N(k\delta)M$$

$$M = H_d / N(k\delta)$$

SHEARED MAGNETIZATION



REPLAY VOLTAGE



VERTICAL RECORDING FIELD REQUIREMENTS

- RING HEAD
- $2 H_c$ AT $y = d + \delta/2$ (CENTER)
- H_y^{peak} AT $x = y + g/2$

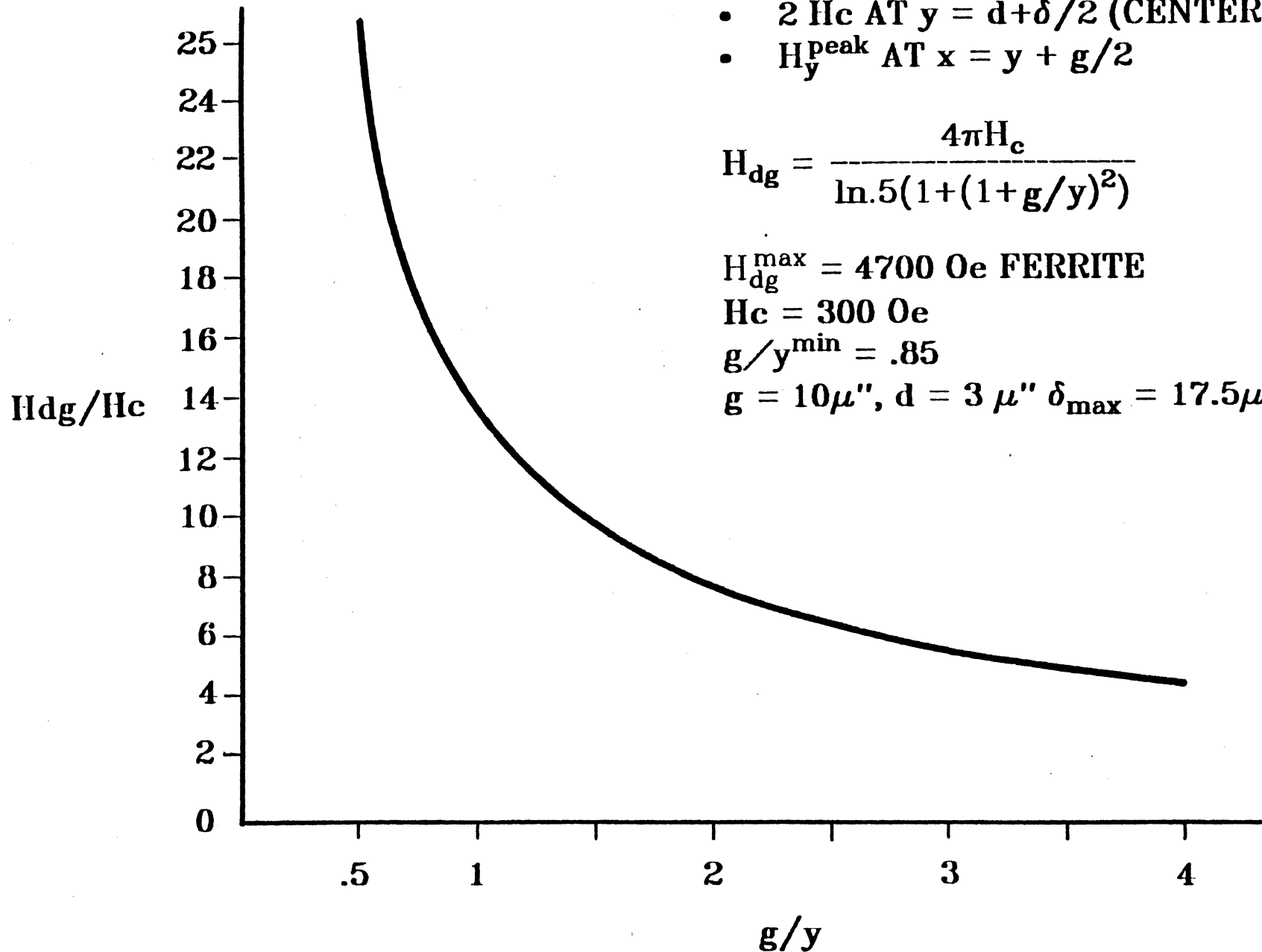
$$H_{dg} = \frac{4\pi H_c}{\ln.5(1+(1+g/y)^2)}$$

$$H_{dg}^{\text{max}} = 4700 \text{ Oe FERRITE}$$

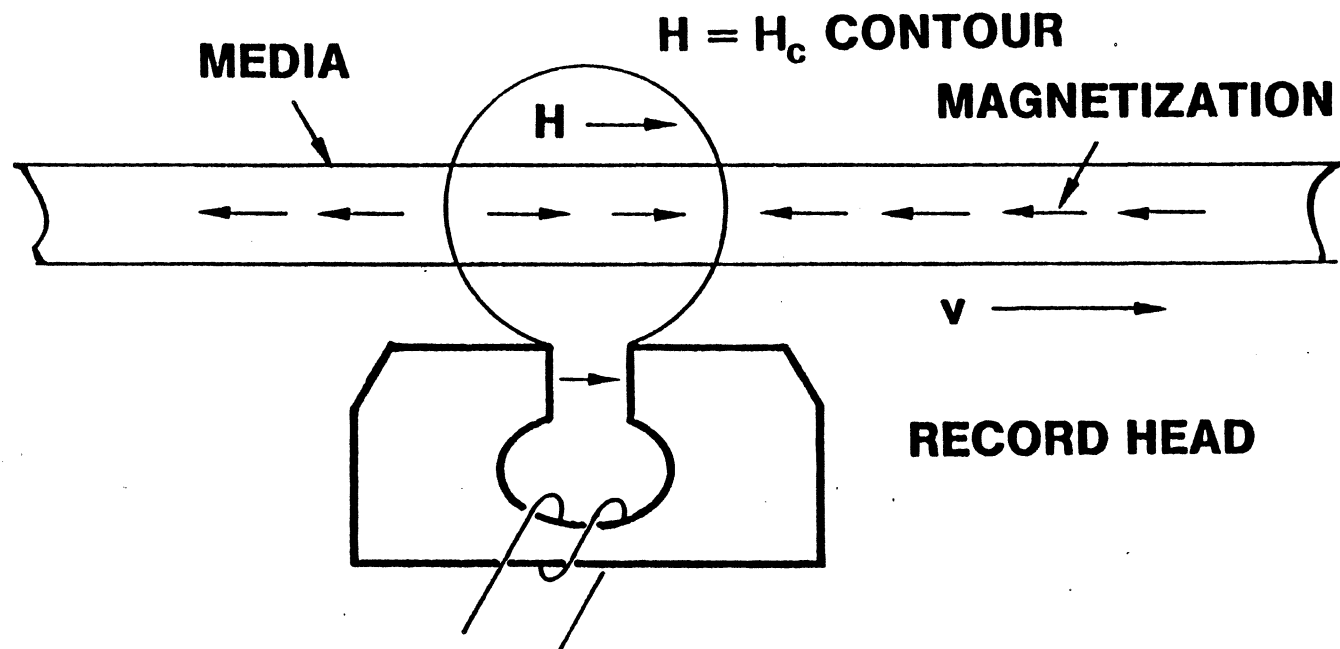
$$H_c = 300 \text{ Oe}$$

$$g/y^{\text{min}} = .85$$

$$g = 10\mu'', d = 3\mu'' \delta_{\text{max}} = 17.5\mu''$$

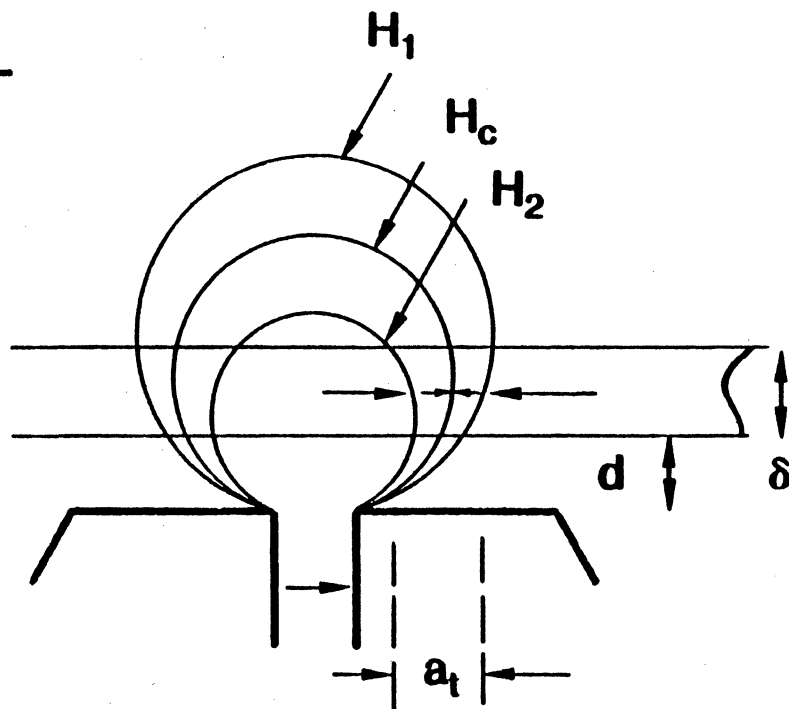
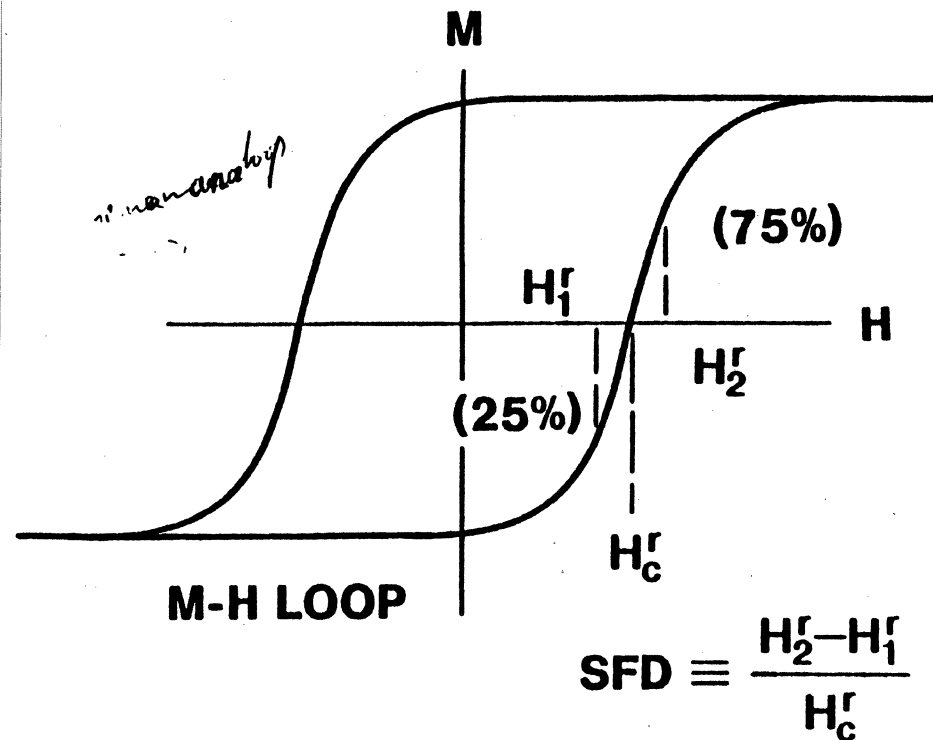


BASIC RECORDING CONCEPTS



BUT REVERSAL LENGTH IS NOT ZERO!

BASIC RECORDING CONCEPTS (Continued)



$a_t \equiv$ TRANSITION WIDTH

SHORT WAVELENGTH VOLTAGE: $V \propto \delta e \frac{-2\pi(a_t + d)}{\lambda}$

a_t DECREASED IF -

- 1) SFD DECREASES $\Rightarrow$ (5%) increase
- 2) HEAD GRADIENT SHARPENS ($d \rightarrow 0$)
- 3) DEMAGNETIZATION IS REDUCED

ROLE OF DEMAGNETIZATION FIELDS

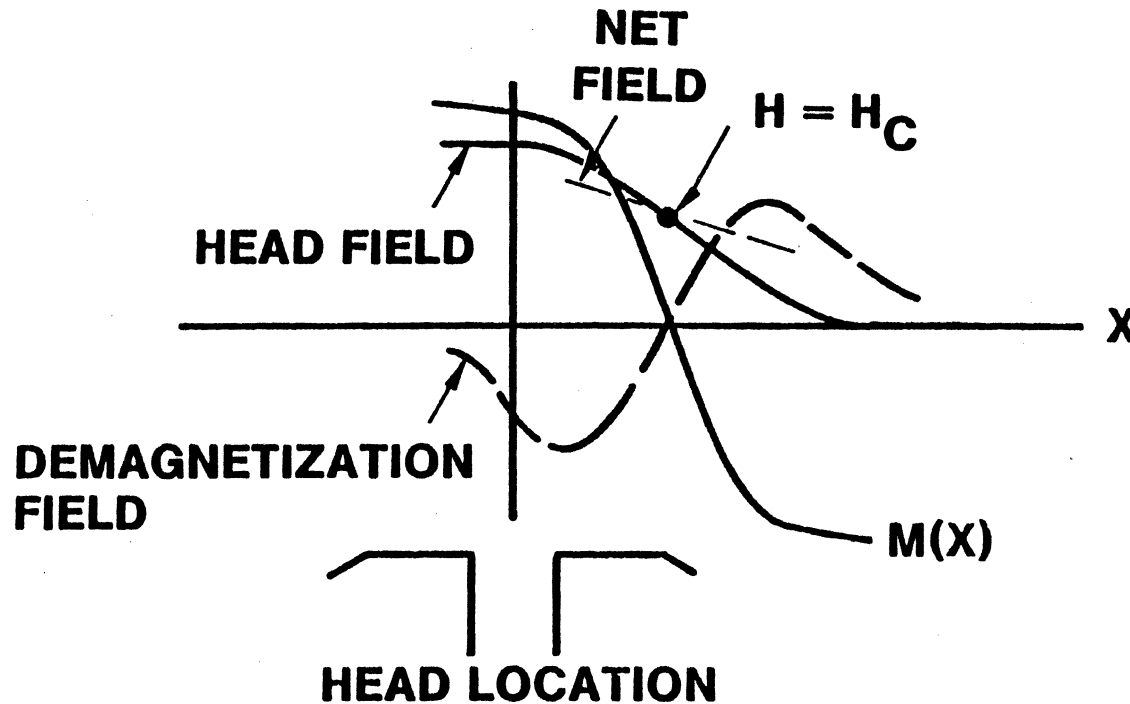
- 1) H_d REDUCES NET FIELD GRADIENT (dH/dx) AT TRANSITION POINT x_0 AND THEREBY BROADENS THE TRANSITION (dM/dx).
- 2) H_d IS ZERO AT TRANSITION CENTER AND (TO FIRST ORDER) DOES NOT MOVE THE TRANSITION.

TECHNIQUES TO SOLVE NON LINEAR $M(x)$ PROBLEM:

- 1) FULL ITERATIVE CALCULATION AT EACH TIME INSTANT
 $H_h \rightarrow M \rightarrow H_d \rightarrow H_{\text{TOTAL}} \rightarrow M_{\text{NEW}} \rightarrow H_d^{\text{NEW}} \rightarrow \dots$ UNTIL CONVERGENCE
- 2) ASSUME SHAPE OF TRANSITION WITH A FEW UNKNOWN PARAMETERS AND SOLVE USING A SIMPLE CRITERION

ARCTANGENT MODEL

$$M(x) = \frac{2}{\pi} M_r \tan^{-1} x/a_t \iff M_k(k) = 2iM_r e^{-ka_t/k}$$



SLOPE CRITERION

$$\frac{dM}{dx} = \frac{dM}{dH} \left[\frac{dH_h}{dx} + \frac{dH_d}{dx} \right]$$

SLOPE MODEL (Continued)

$$\frac{dM}{dx} = \frac{2}{\pi} \frac{M_r}{a}, \quad \frac{dM}{dH} = \frac{M_r}{H_c(1-S^*)}$$

$$\frac{dH_h}{dx} = \frac{QH_c^r}{d}, \quad \frac{dH_d}{dx} = -\frac{M_r \delta}{\pi a^2}$$

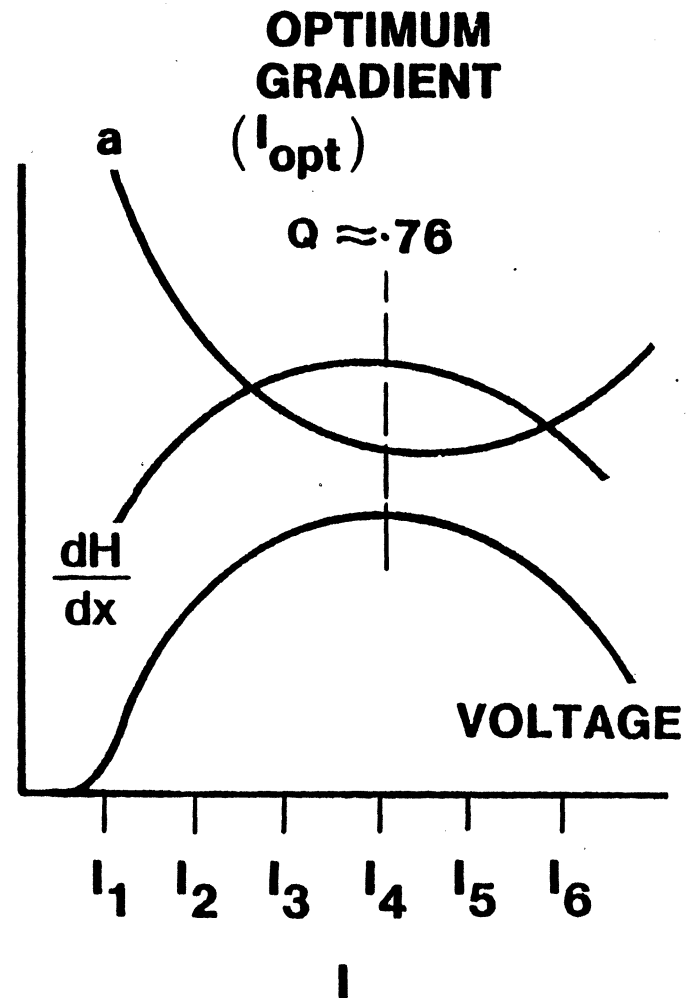
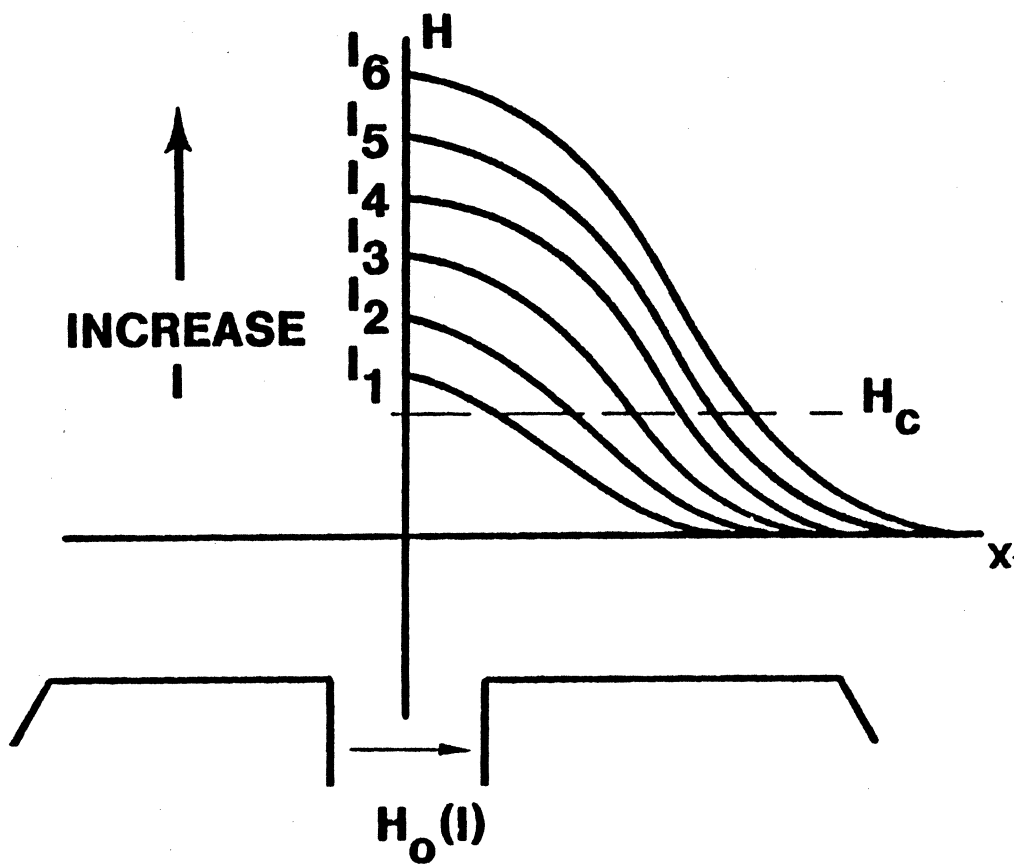
SOLVING SLOPE CRITERION YIELDS

$$a = \frac{d(1-S^*)}{\pi Q} + \left\{ \left(\frac{d(1-S^*)}{\pi Q} \right)^2 + \frac{M_r \delta d}{\pi Q H_c} \right\}^{1/2}$$

SHARP GRADIENT	$Q \rightarrow \infty$	$\Rightarrow$	$a \rightarrow 0$
ZERO SPACING	$d \rightarrow 0$	$\Rightarrow$	$a \rightarrow 0$
SHARP LOOP	$S^* \rightarrow 1$	$\Rightarrow$	a DECREASES
REDUCE DEMAG	$M_r/H_c \rightarrow 0$	$\Rightarrow$	a DECREASES
REDUCE THICKNESS	$\delta \rightarrow 0$	$\Rightarrow$	a DECREASES

CURRENT OPTIMIZATION - SHORT WAVELENGTHS

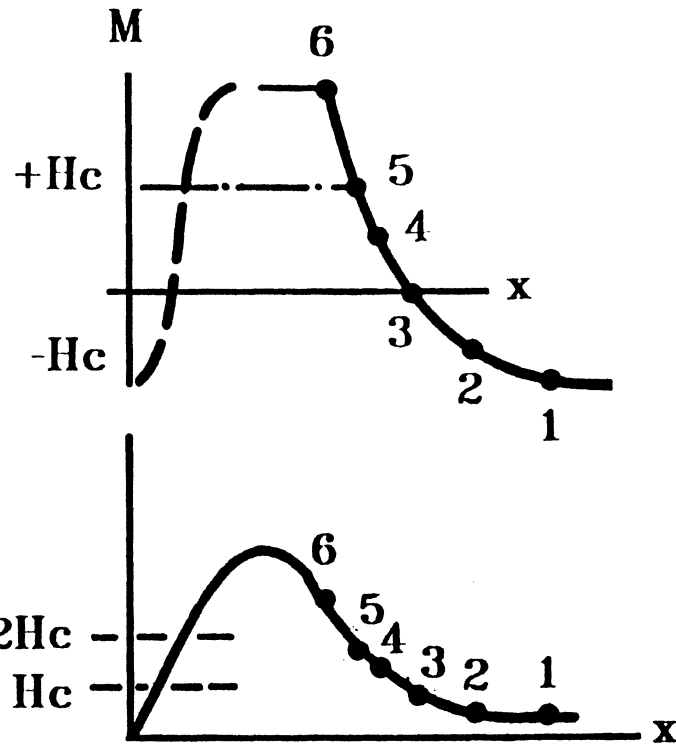
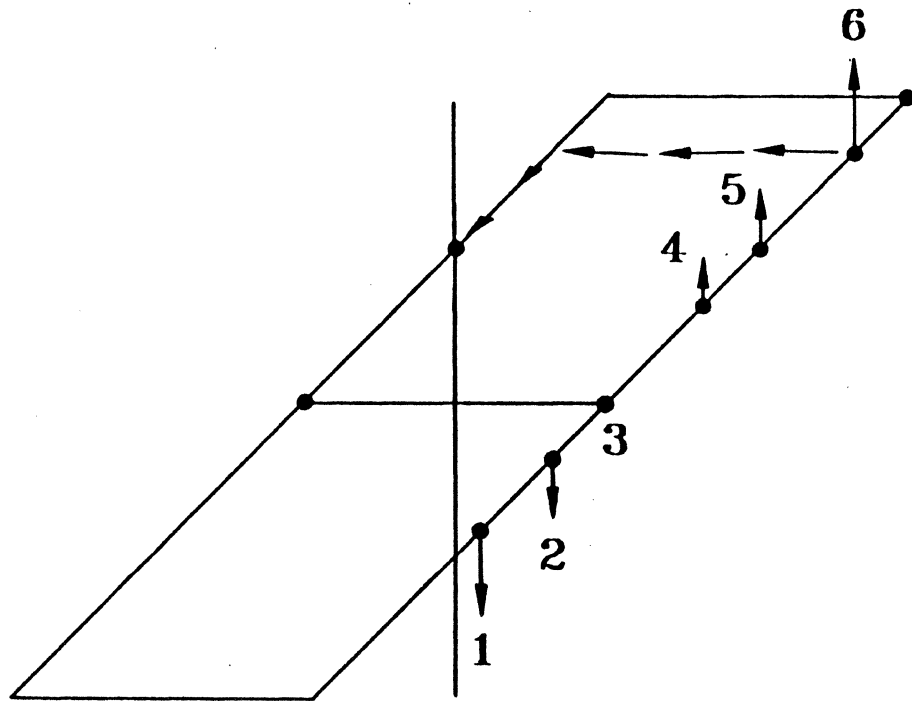
$$V \propto M_r k \delta e^{-ka}$$



PERPENDICULAR RECORDING

THIN MEDIA

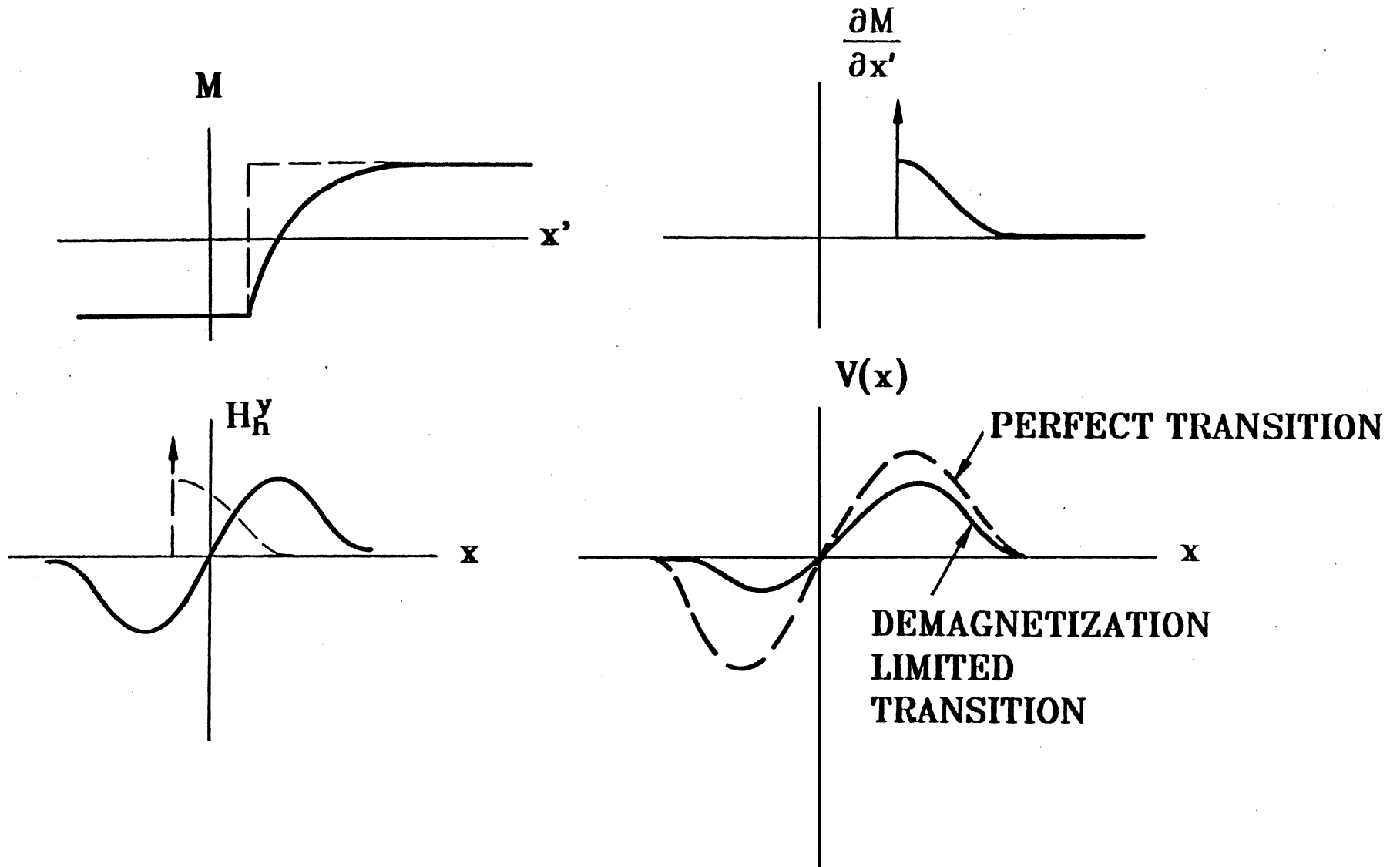
$$H_D = -M \text{ FOR ALL } M(x)$$



RING HEAD

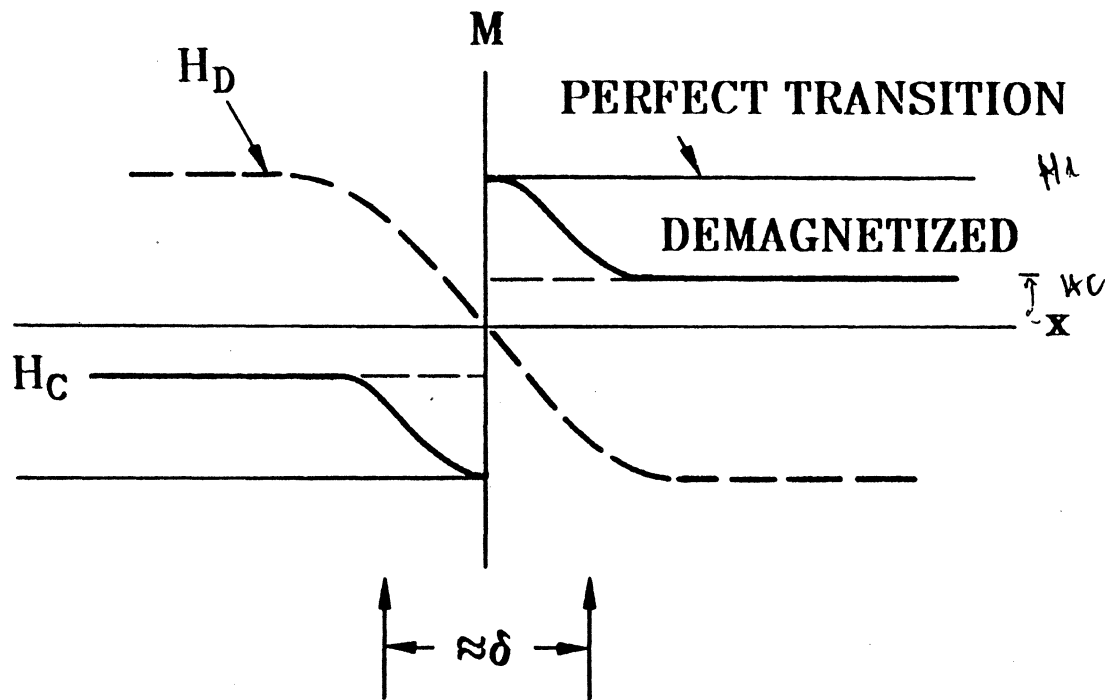
ISOLATED PULSE

$$V(x) \propto \int_{-\infty}^{\infty} \frac{\partial M}{\partial x'} \cdot H_h^y(x+x')$$

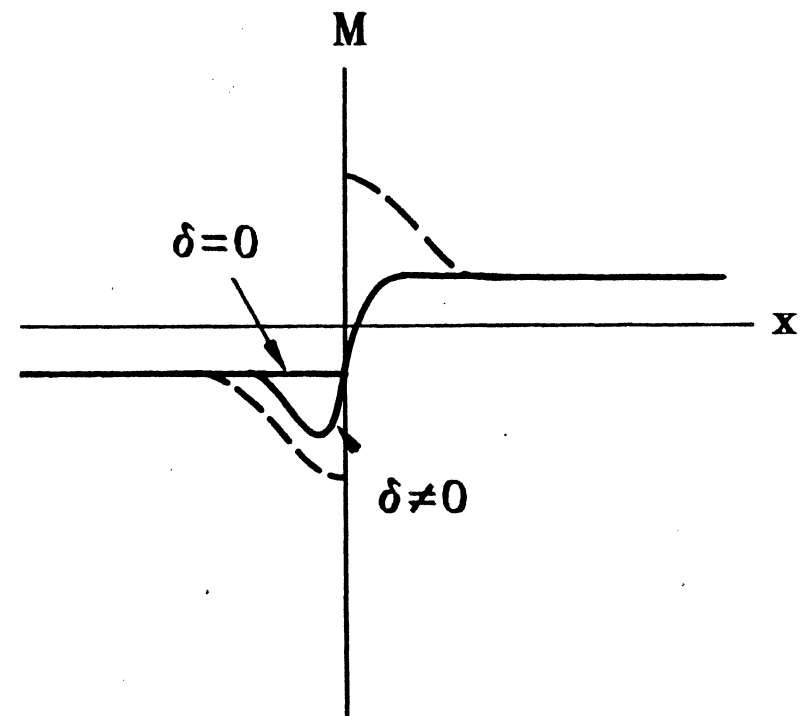


THICK MEDIA

$$H_D \simeq -\frac{2M}{\pi} \text{TAN}^{-1} 2x/\delta$$



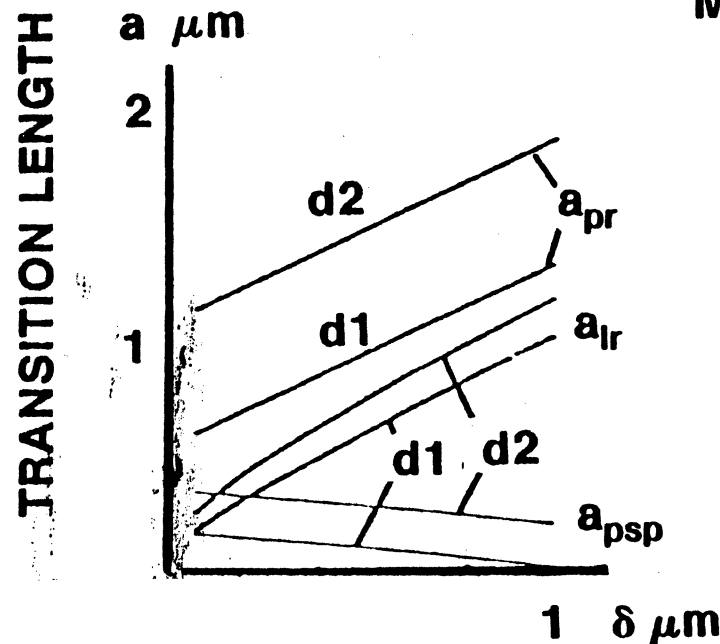
SIMPLE DEMAGNETIZATION



RECORD PROCESS

COMPARISONS

		HEAD GRADIENT	DEMAG	OVERALL
LONGITUDINAL	RING { PROBE	GOOD	GOOD (THIN)	GOOD
		POOR	GOOD (THICK)	MIXED
PERPENDICULAR		GOOD	GOOD (THICK)	GOOD



MIDDLETON & WRIGHT
~~IEEE~~ CONF.
 IEEE 1982

$$d1 = 0.25 \mu\text{m}$$

$$d2 = 0.5 \mu\text{m}$$

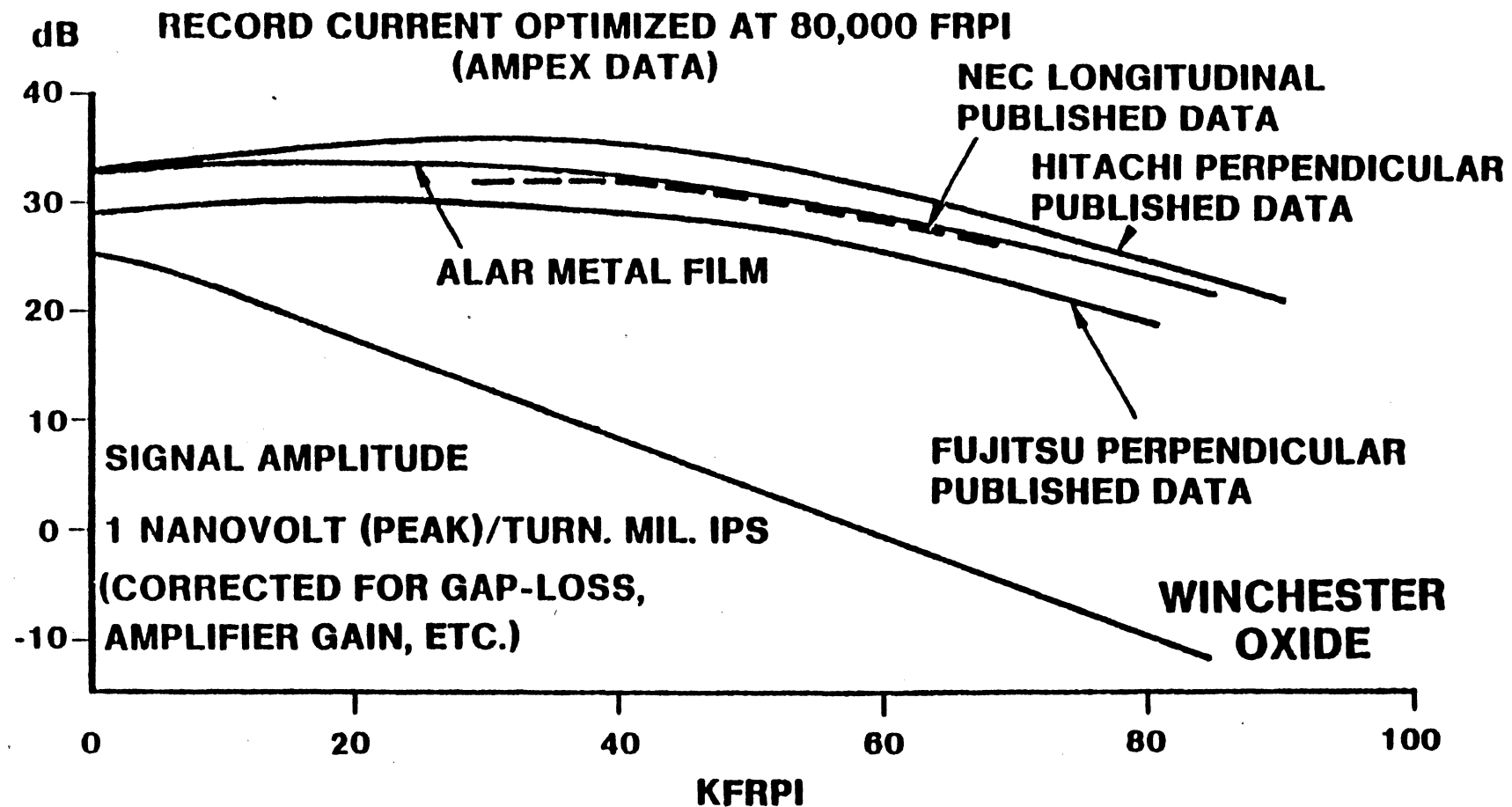
(THICKNESS)

HIGH DENSITY COMPARISON OF RECORDING MEDIA

MANGANESE-ZINC FERRITE HEAD, $g = 12\mu$ "

FLYING HEIGHT $\leq 4\mu$ "

RELATIVE VELOCITY = 500 IPS



REVIEW OF UNITS

SI (MKS)

$$B = \mu_0 (H+M)$$

B: TESLA

H: AMPS/METER

M: AMPS/METER

$$\mu_0 = 4\pi \times 10^{-7} \text{ HENRY'S METER}$$

C.G.S.

$$B = H + 4\pi M$$

$$\text{GAUSS } 1 \text{ TESLA} = 10^4 \text{ G}$$

$$\text{Oe } 80 \text{ A/M} = 1 \text{ Oe}$$

$$\text{GAUSS } 1 \text{ kA/M} = 1 \text{ G (emu/cc)}$$

E.G. FIELD H FOR $N = 10$, $I = 30 \text{ mA}$, $g = 30 \mu''$

$$H = \frac{NI}{g} = 400 \text{ kA/M OR } 5000 \text{ Oe}$$

MAGNETIZATION $\gamma\text{Fe}_2\text{O}_3 \mu \approx 70 \text{ emu/g}$, $\rho \sim 4.5 \text{ g/cc}$

$$M_p = 70 \times 4.5 \sim 350 \text{ emu/cc}$$

$$M_{\text{TAPE}} = pM_p = \frac{1}{3} \times 350 \sim 110 \text{ emu/cc} \sim 110 \text{ G OR } 110 \text{ kA/M}$$

$$B_r = 4\pi M \cong 1500 \text{ G or } .15 \text{ TESLA}$$

Thin Magnetic Phenomena and Processes

Robert White
CDC

MAGNETIC THIN FILMS

- I. Introduction**
- II. Intrinsic Magnetic Properties of Metal Films**
 - A. Magnetization**
 - B. Anisotropy**
 - C. Magnetostriction**
 - D. Magnetoresistivity**
 - E. Magnetic Resonance**
 - F. Magnetooptics**
- III. Extrinsic Magnetic Properties of Metal Films**
 - A. Coercivity**
 - B. Transition Length**
- IV. Thin Film Media**
 - A. Substrate**
 - B. Magnetic Film Fabrication**

Plating	}	Horizontal
Sputtering	}	Vertical
Evaporation	}	Magnetooptical
- V. Thin Film Heads**
 - A. Critical Parameters**
 - B. Permalloy**
 - C. Fabrication**
 - D. Domain Effects**
 - E. Magnetoresistive Heads**

I. INTRODUCTION

SELF-DEMAGNETIZATION

$$H_d(\vec{r}) = \int \frac{\nabla' \cdot \vec{M}(\vec{r}') (\vec{r} - \vec{r}')}{|\vec{r} - \vec{r}'|^3} d^3r'$$

$$M_x(X) = - \frac{2M_r}{\pi} \tan^{-1}(x/a)$$

$$H_{dx}(x,0)_{\max} = H_c$$

$$a_{\min} = 2 \frac{M_r \delta}{H_c}$$

$$PW_{50} = \sqrt{g^2 + 4(d+a)(d+a+\delta)}$$

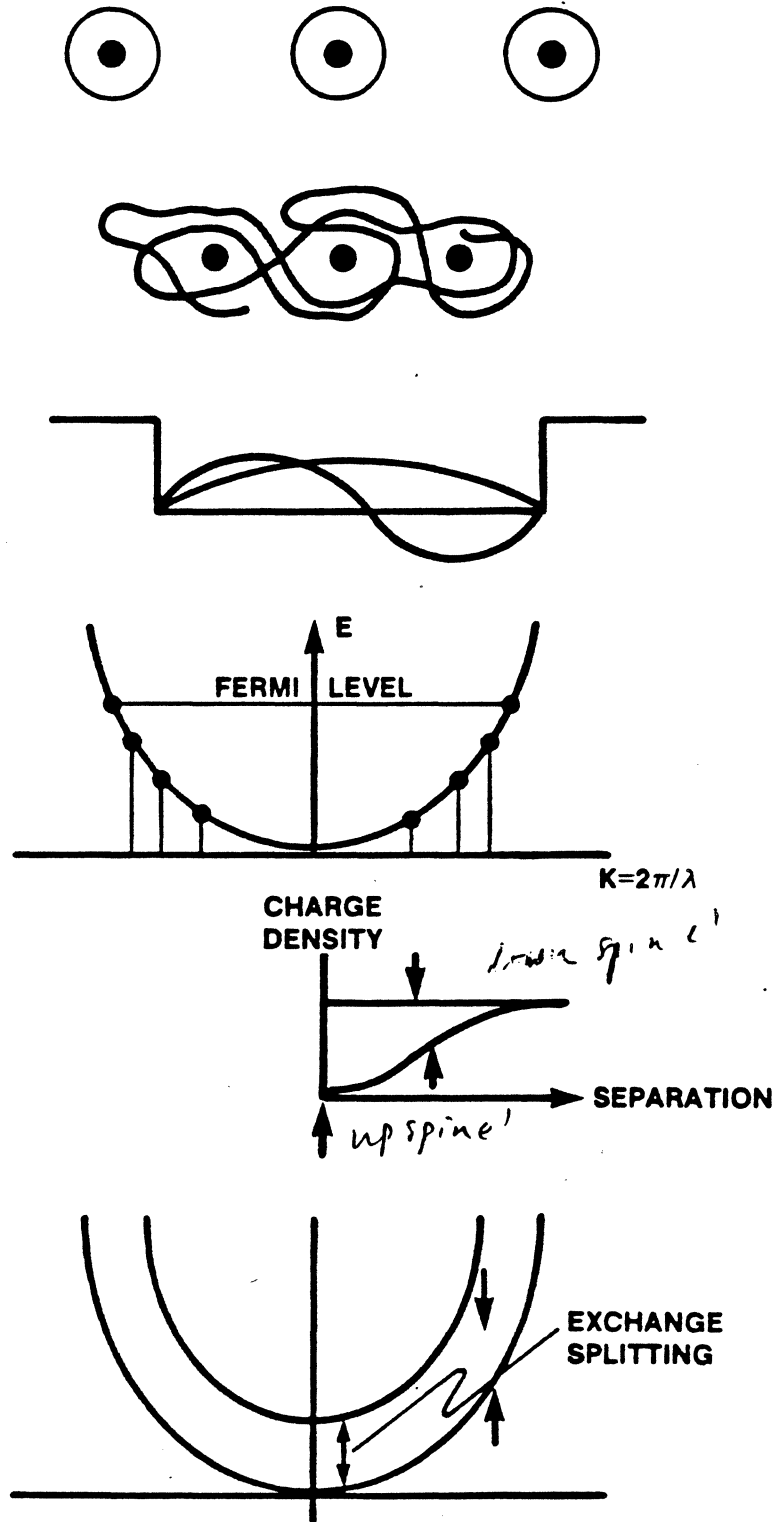
increase H_c (limited by head)

decrease δ (limited by defects, durability, etc.)

maintain $M_r \delta$

II. INTRINSIC PROPERTIES

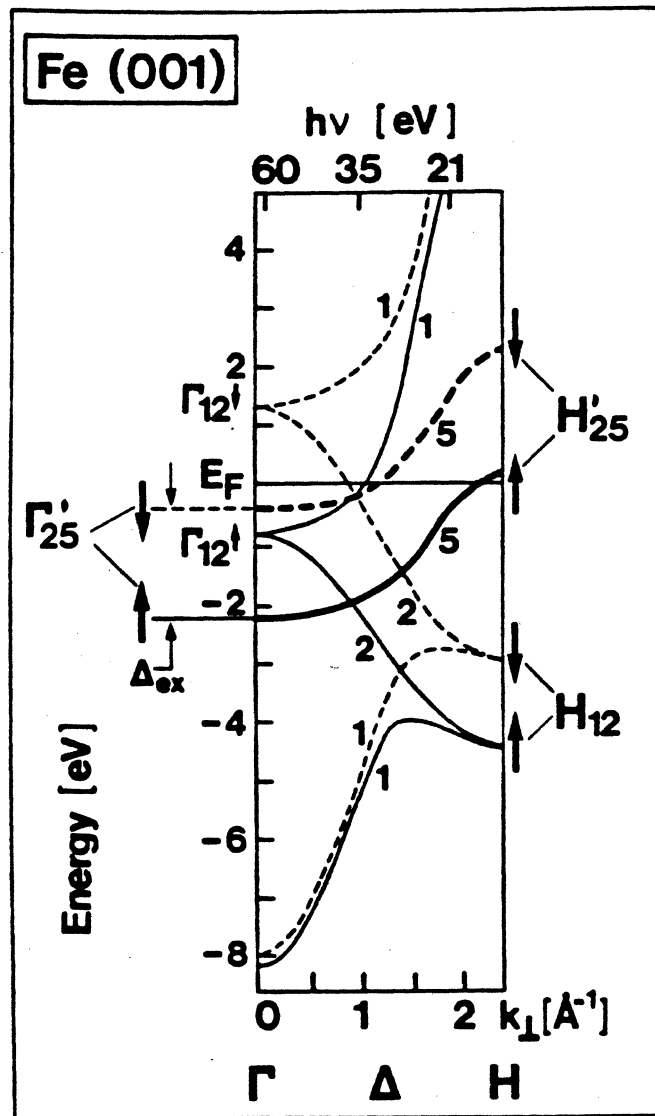
A. MAGNETIZATION



$$\mu = (n^{\uparrow} - n^{\downarrow}) \mu_B$$

$$\text{CHEMICAL VALENCE} = Z = n^{\uparrow} + n^{\downarrow}$$

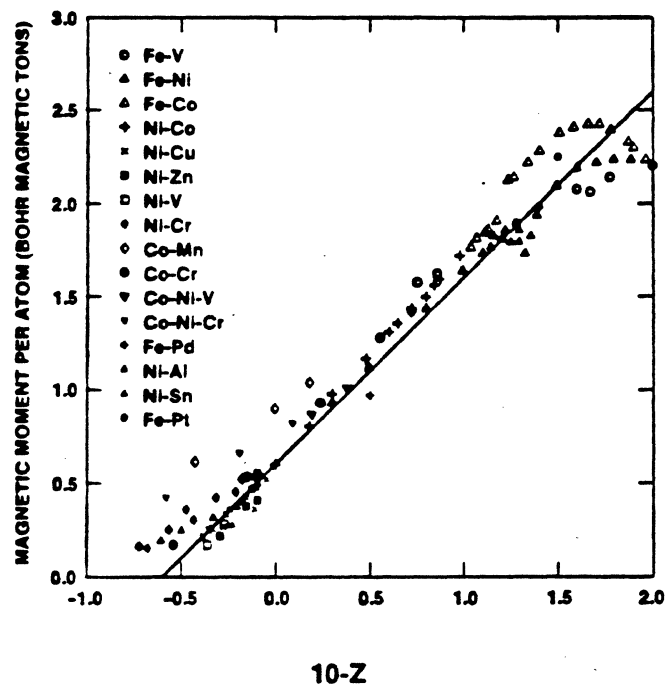
e.g. Fe $3d^6 4s^2$



$$\left. \begin{array}{l} n_d^{\uparrow} = 5 \\ n_s^{\uparrow} = 0.3 \end{array} \right\} \text{HOLDS FOR ELEMENTS TO RIGHT OF Fe AS WELL}$$

$$\therefore \mu/\mu_B = 2(n_d^{\uparrow} + n_s^{\uparrow}) - Z = 10.6 - Z$$

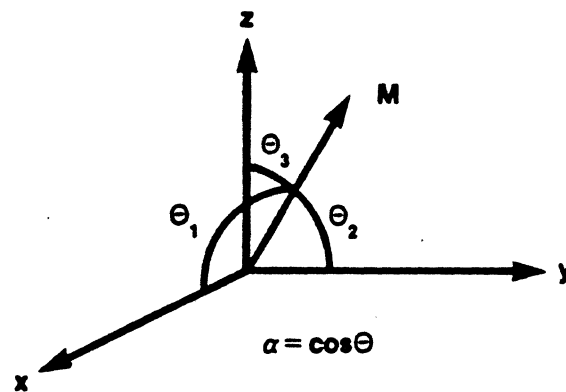
CHANGE Z BY ALLOYING



SLATER-PAULING CURVE

B. ANISOTROPY

Fe	Co	Ni
bcc	hcp	fcc



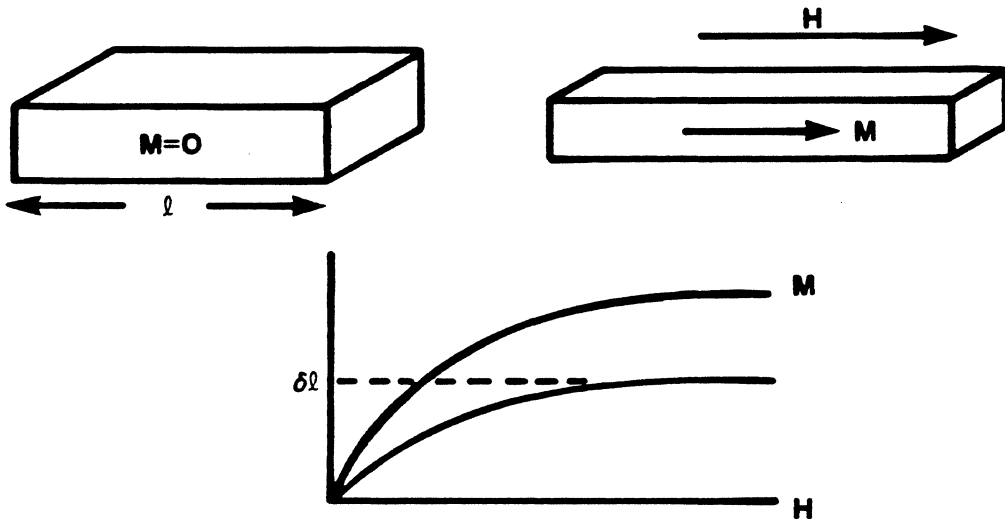
$$E_A = K_1 (\alpha_1^2 \alpha_2^2 + \alpha_2^2 \alpha_3^2 + \alpha_3^2 \alpha_1^2)$$

$$K_1 (\text{Fe}) = 4.6 \times 10^5 \text{ erg/cm}^3 \quad (100)$$

$$K_1 (\text{Ni}) = -0.56 \times 10^5 \text{ erg/cm}^3 \quad (111)$$

By alloying
Fe & Ni we
can find a comp
where anisotropy
is zero.

C. MAGNETOSTRICTION



$$\text{MAGNETOSTRICTION} = \delta l / l$$

PHYSICALLY $E_{me} = \frac{\partial E_A}{\partial e} e$ $e = \text{STRAIN}$

PHENOMENOLOGICALLY $E_{me} = B_1(\alpha_1^2 e_{xx} + \alpha_2^2 e_{yy} + \alpha_3^2 e_{zz}) + \dots$

$$\frac{\delta l}{l} = \frac{3}{2} \lambda_{100} (\alpha_1^2 \beta_1^2 + \alpha_2^2 \beta_2^2 + \alpha_3^2 \beta_3^2 - \frac{1}{3}) + \dots$$

α 's DEFINE DIRECTION OF MAGNETIZATION
 β 's DEFINE DIRECTION OF ELONGATION

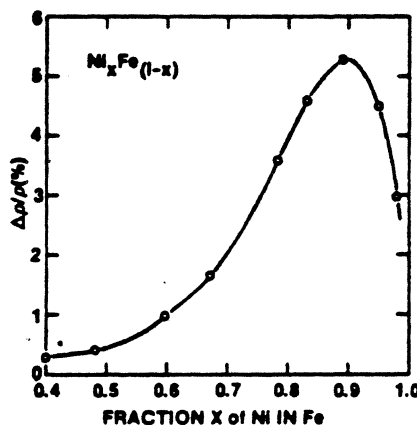
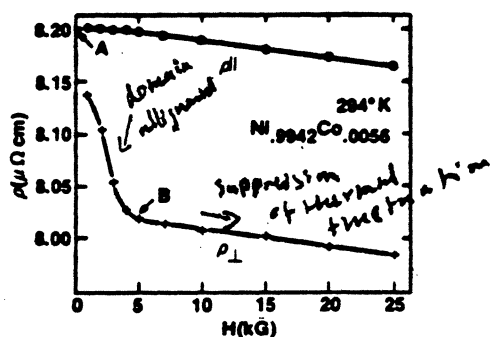
$$\lambda_{100} (\text{Fe}) = 20.7 \times 10^{-6}$$

$$\lambda_{100} (\text{Ni}) = -45.9 \times 10^{-6}$$

Alloy Fe & Ni we
 can get zero magnetostriction
 may not be same comp as
 zero anisotropy

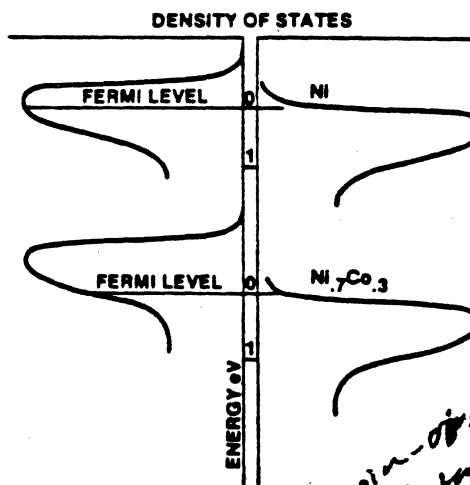
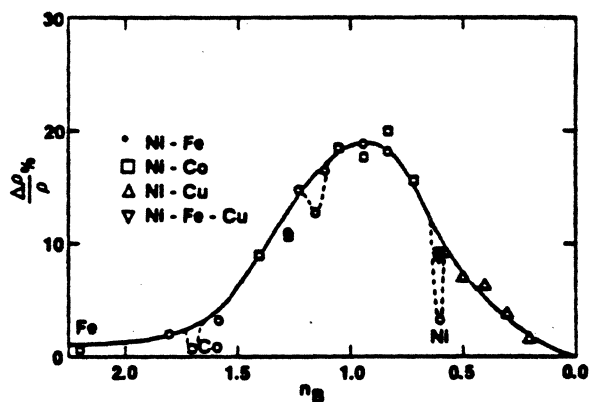
D. ANISOTROPIC MAGNETORESISTANCE

zero magnetostatic
zero extraordinary
Hall effect
Voltage & mag.



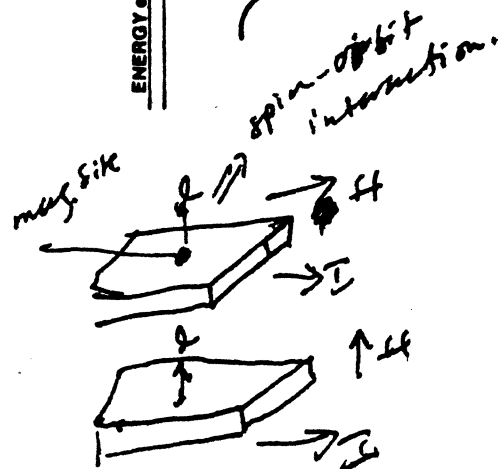
increase
in field suppresses
the mag. vector
→ lower resistance

max not correlated to E_F



$$\mathcal{H}_{\text{spin-orbit}} = \lambda \vec{L} \cdot \vec{S}$$

$$\frac{\Delta\rho}{\rho} = i\left(\frac{\lambda}{E}\right)$$



E. MAGNETIC RESONANCE



$$\begin{aligned}\text{ANGULAR MOMENTUM} &= \vec{S} \hbar \\ \text{MAGNETIC MOMENT} &= 2\mu_B \vec{S}\end{aligned}$$

TORQUE = RATE OF CHANGE OF ANGULAR MOMENTUM

$$\vec{r} \times \vec{F} = \frac{d\vec{L}}{dt}$$

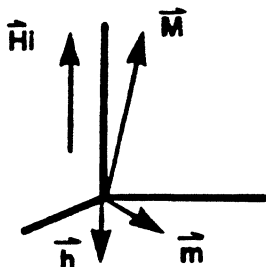
$$\gamma \vec{M} \times \vec{H} = \frac{d\vec{M}}{dt}$$

$$\gamma = 2\mu_B/\hbar$$

$$\vec{H} = \vec{H}_i + \vec{h} e^{i\omega t}$$

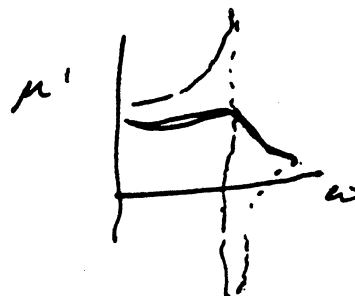
$\vec{H}_i$ = Internal field due to anisotropy

$$\vec{M} = \vec{M}_s + \vec{m} e^{i\omega t}$$



$$m \ll M_s$$

$$\vec{m} \times \vec{M}_s = 0$$



SOLVE FOR $\vec{M}$ AND EXPRESS AS $\vec{B} = \hat{\mu} \vec{H}$

$$\hat{\mu} = \begin{pmatrix} \mu & -i\kappa & 0 \\ i\kappa & \mu & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\mu = 1 + \frac{\omega_0 \omega_M}{\omega_0^2 - \omega_M^2}$$

$$\begin{aligned}\omega_0 &= \gamma H_i \\ \omega_M &= \gamma 4\pi M_s\end{aligned}$$

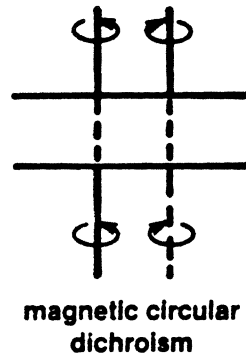
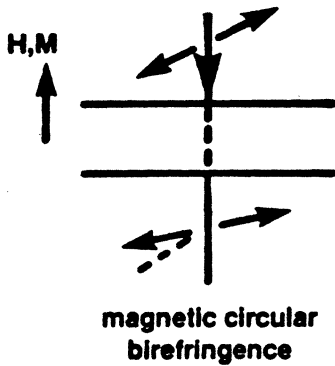
$$\mu(0) \omega_0 \sim \omega_M$$

F. MAGNETO-OPTICS

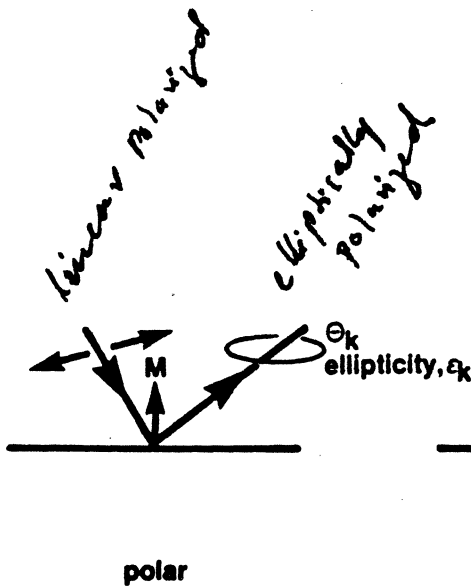
⇒ high freq. form of hall effect.

Circular Polarized

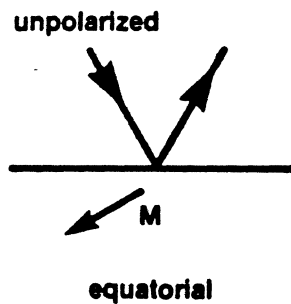
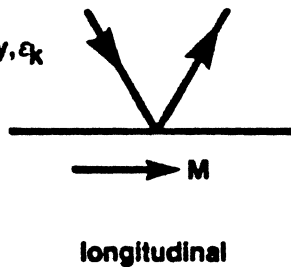
left & right polarized are attenuated to diff. extent



FARADAY



does not couple with mag. field



KERR

The current from the mag. field couples with the polarized light

ALL MO PHYSICS CONTAINED IN CONDUCTIVITY TENSOR

$$\sigma = \begin{pmatrix} \sigma_{xx} & \sigma_{xy} & 0 \\ -\sigma_{xy} & \sigma_{yy} & 0 \\ 0 & 0 & \sigma_{zz} \end{pmatrix}$$

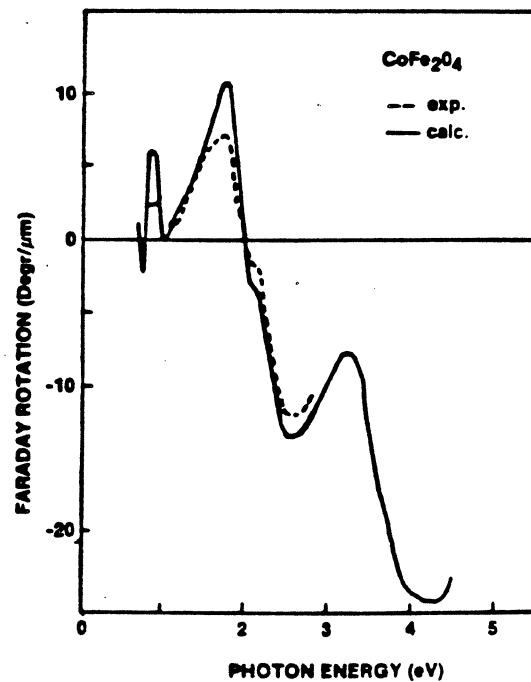
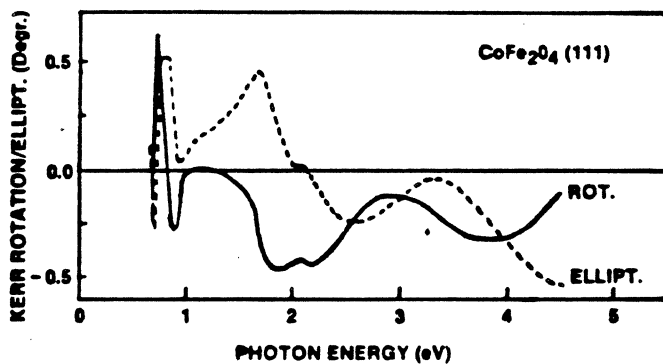
$$\Theta_F = -\frac{2\pi l}{cn} \sigma'_{xy}$$

$$\Theta_K = \frac{2\lambda}{cn} \sigma''_{xy}$$

$$\alpha^+ - \alpha^- = \frac{4\pi}{c} \sigma''_{xy}$$

$$\epsilon_K \sim \sigma'_{xy} \text{ ellipticity}$$

Note: at DC $\sigma'_{xy}(0) = \text{RB (Hall)}$
 at $\omega_0 \ll \omega < \text{optical}$ $\Theta_F = \frac{\omega_M l}{2c/n}$ (microwave devices)

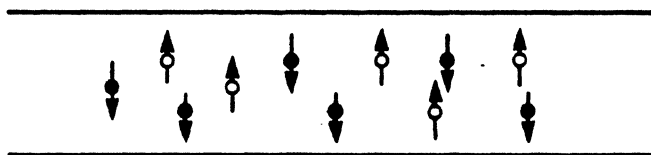


MAGNETO-OPTIC MEDIA

1973 - Discovery of amorphous RE-TM films

	Fe	Co	Ni
Gd	⊥	⊥	⊥
Tb	⊥	⊥	
Dy	⊥	⊥	
Ho	⊥	⊥	⊥
Er	⊥		

*Temp effect diff. on the
rare earth vs transition
metal atoms.
at some temp.
the moments from
RE & TE cancel
each other
⇒ compensation
temp.*

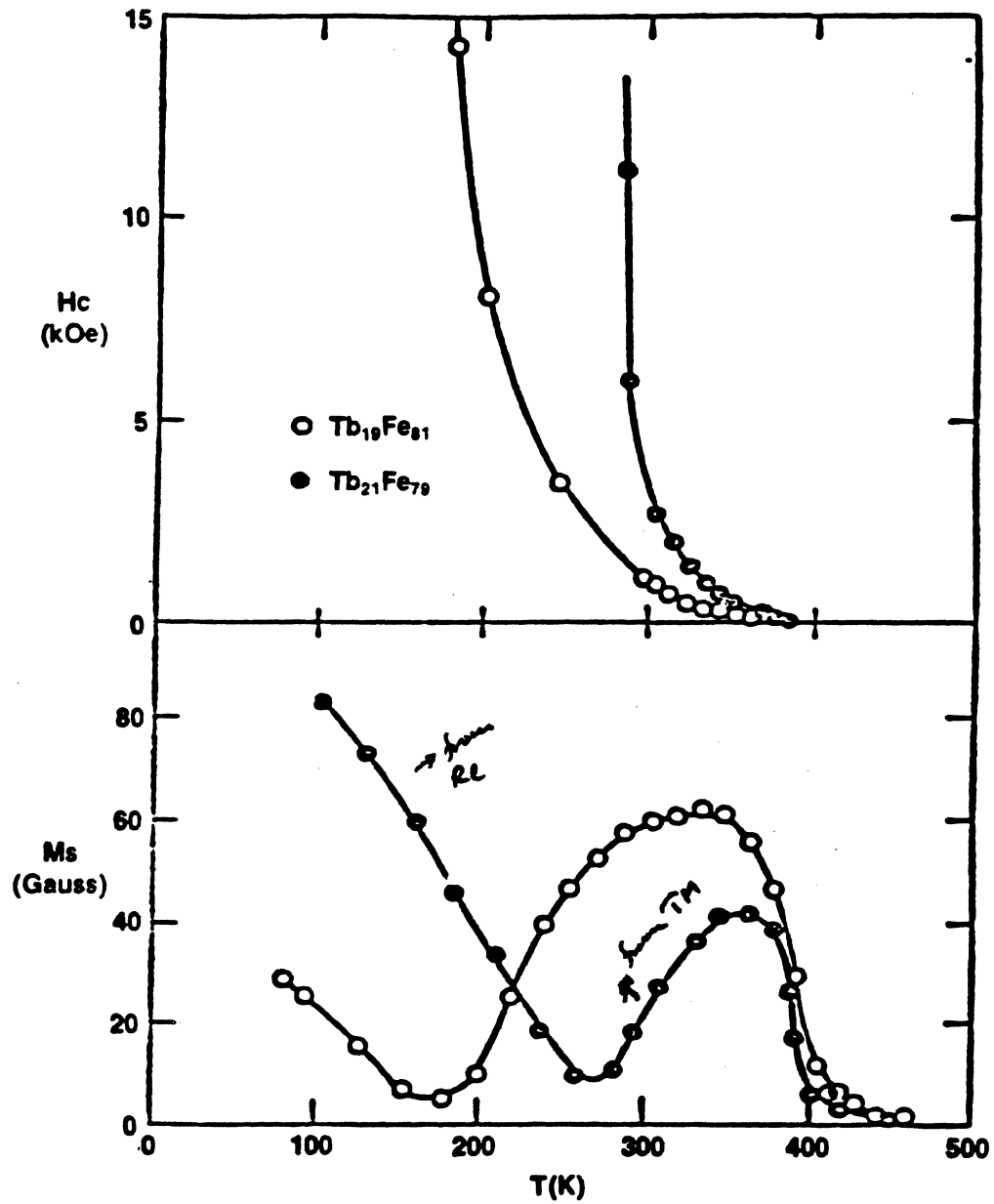


short range order — ferrimagnetic { compensation point
vertical anisotropy

Fe governs
magneto optic effect

Temp changes with
composition of RE & TM

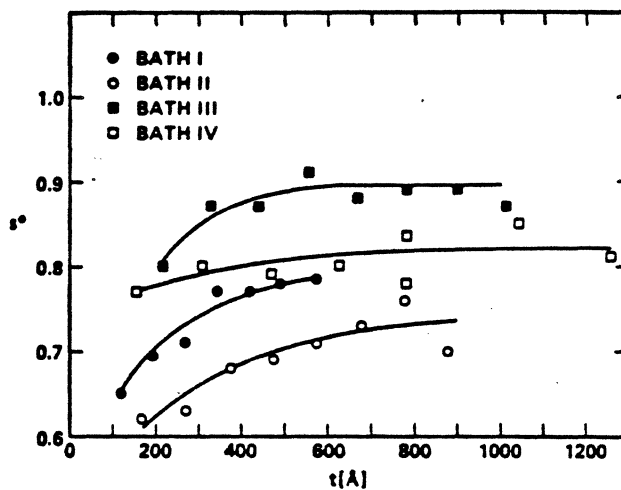
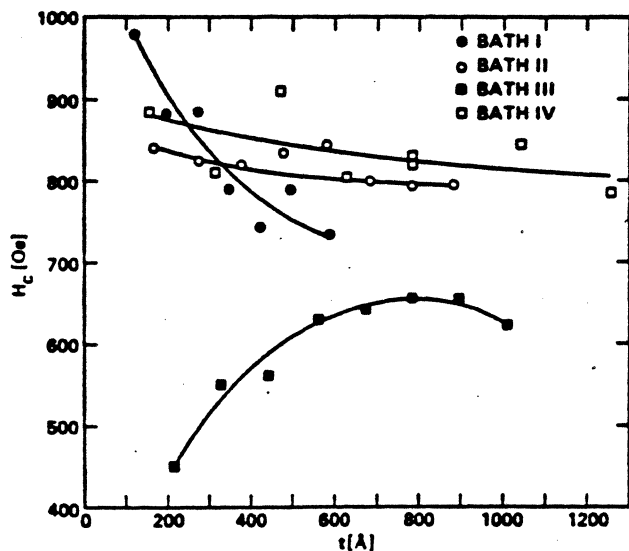
at Temp $\Rightarrow$ coercivity $\rightarrow \infty$



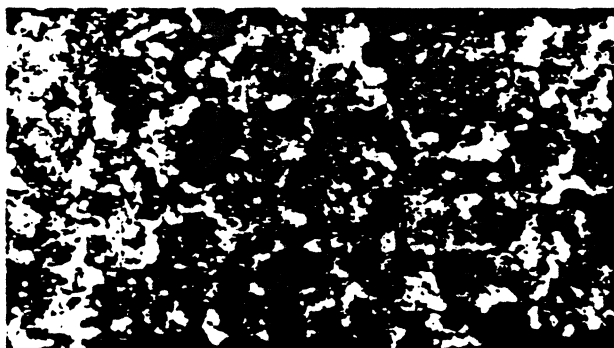
$$\text{coercivity} \sim \frac{2K}{M_s}$$

III. EXTRINSIC PROPERTIES

A. COERCIVITY



Co-P Films

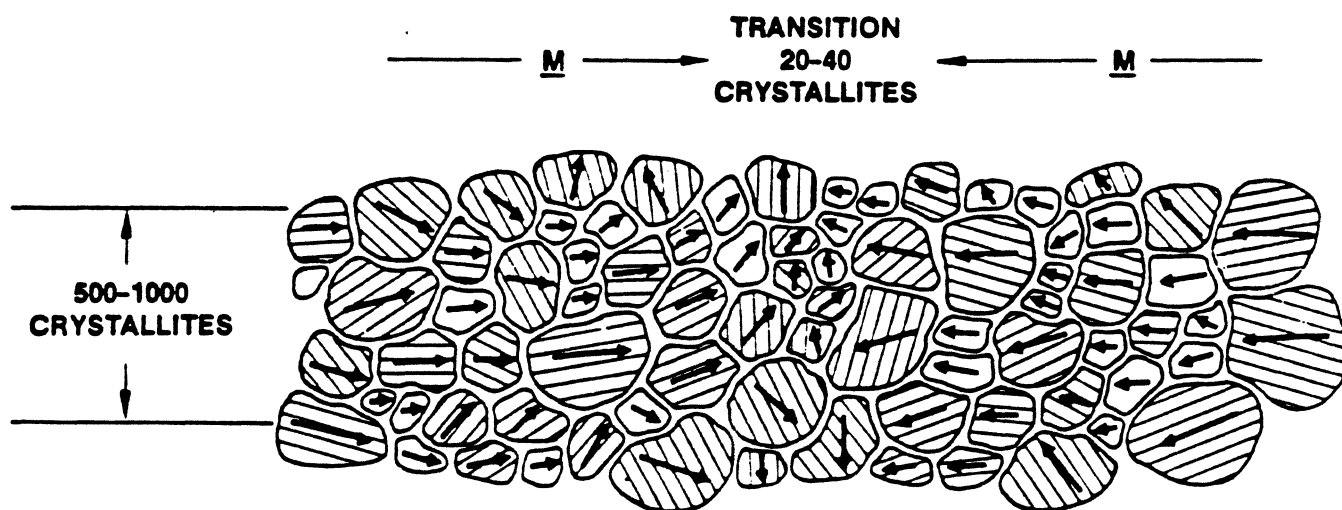


Bath III
Poorly Developed Grains



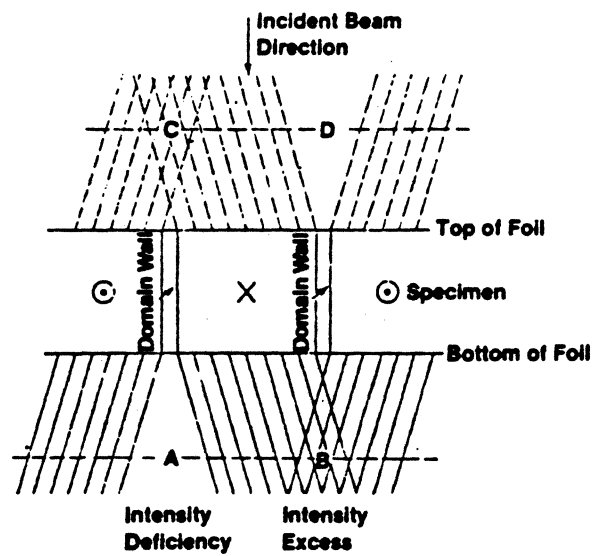
Baths I, II
Well Developed Grains

METAL FILM: STRONGLY INTERACTING "PARTICLES"

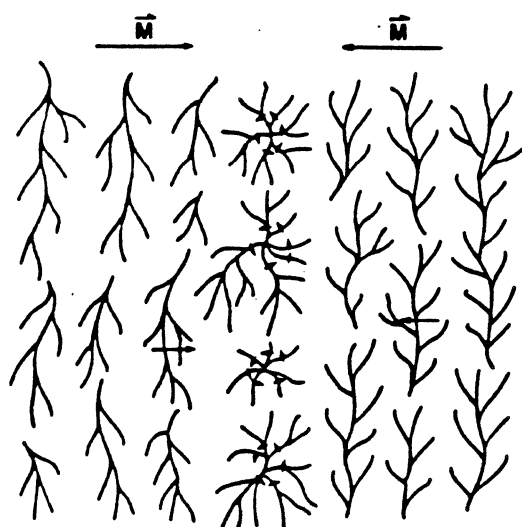
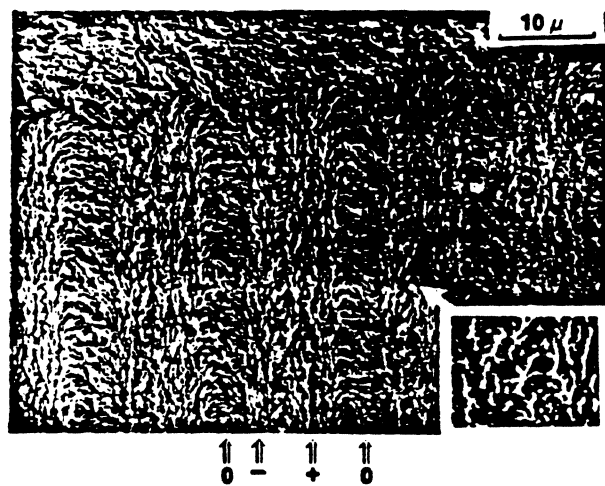


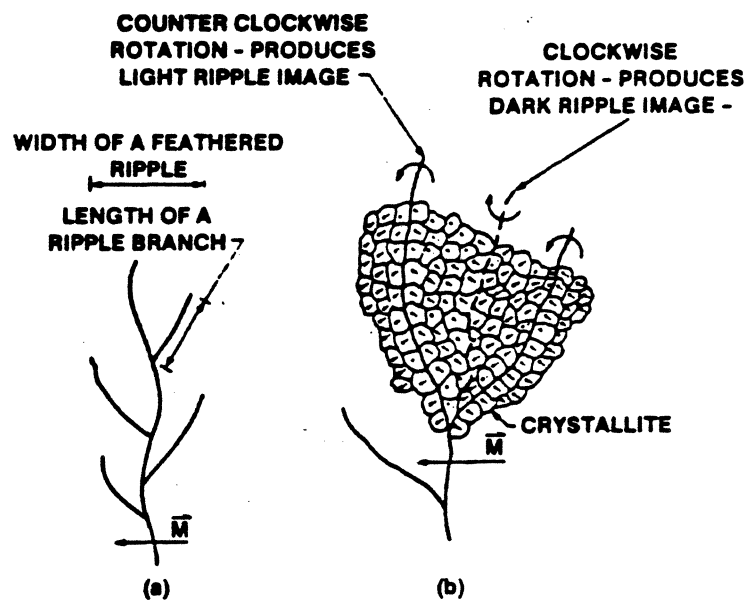
LORENTZ MICROSCOPY

Out-of-Focus Method



B. TRANSITION LENGTH





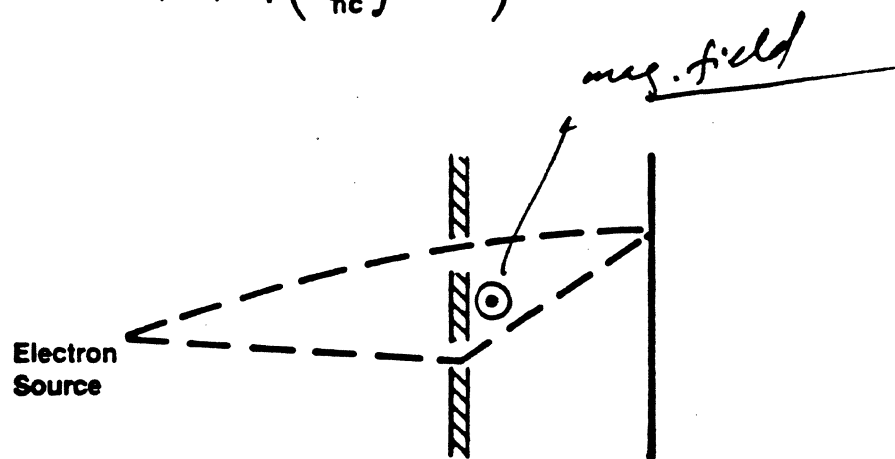
Interactions - Clusters - Ripple

ELECTRON HOLOGRAPHY

$$\vec{B} = \nabla \times \vec{A}$$

momentum $\vec{p} = \vec{p} - \frac{e}{c} \vec{A}$

wave function $\psi = \psi \exp\left(i \frac{e}{\hbar c} \int \vec{A} \cdot d\vec{s}\right)$



$$\text{"Magnetic" Phase Shift} = \frac{e}{\hbar c} \underbrace{\int \vec{A} \cdot d\vec{s}}_{\substack{\text{flux} \\ (\text{area of the } \Delta \varphi)}} = \pi \frac{\Phi}{\Phi_0}$$

Aharonov & Bohm (1959)

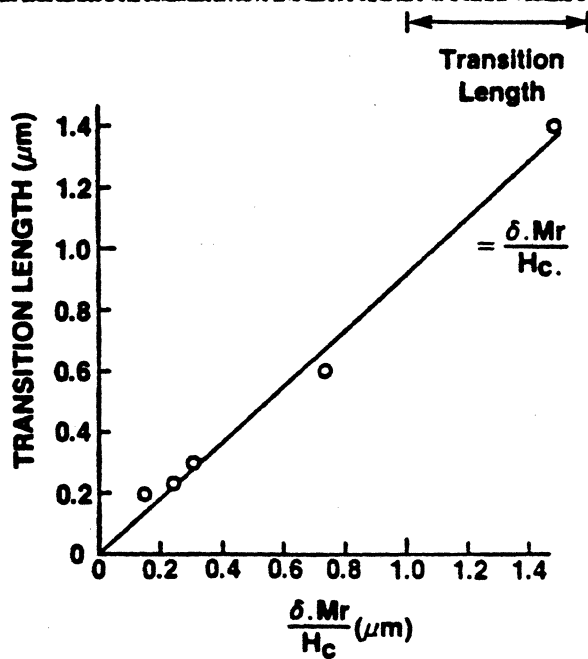
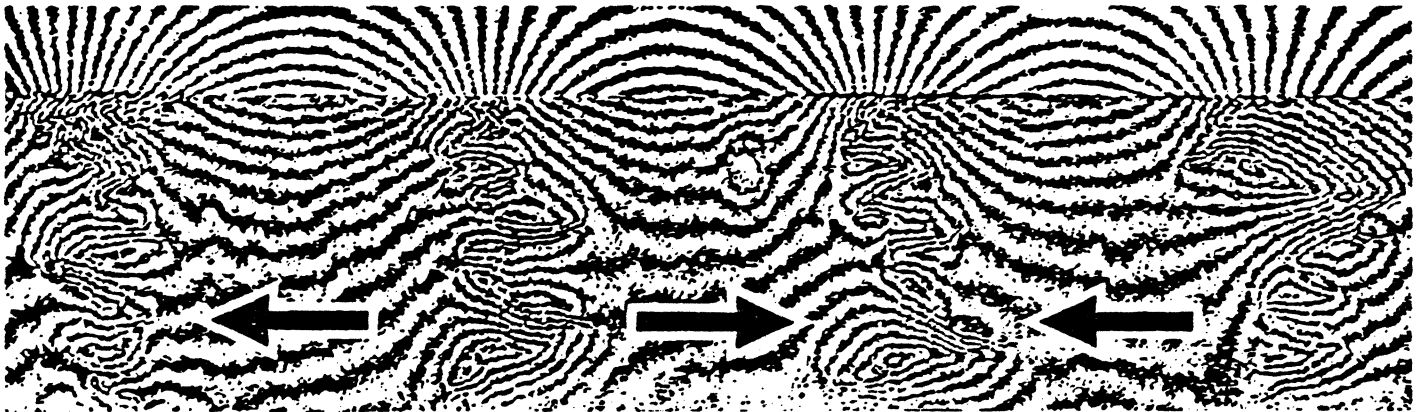
Cohen (1967)

Tonomura (1972)

RECORDED TRANSITION:

400x Co-film

Note Free Space
Contours



AI SUBSTRATE EVOLUTION

	flying height	coating thickness	substrate	
2314	100 μ''	85 μ''	50 mil	lathe finish
3330	75	50	75	radial polish
3350	41	41	75	circumferential polish (1 μ'')
3380	10-12	23	150	diamond turned (0.2-0.4 μ'')

Implications of zig-zag wall:

• Limitation on FCI

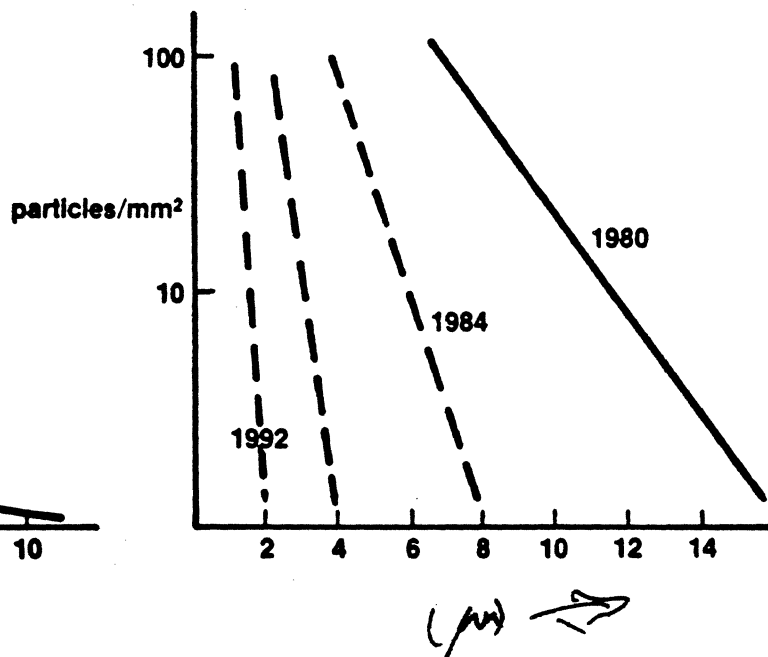
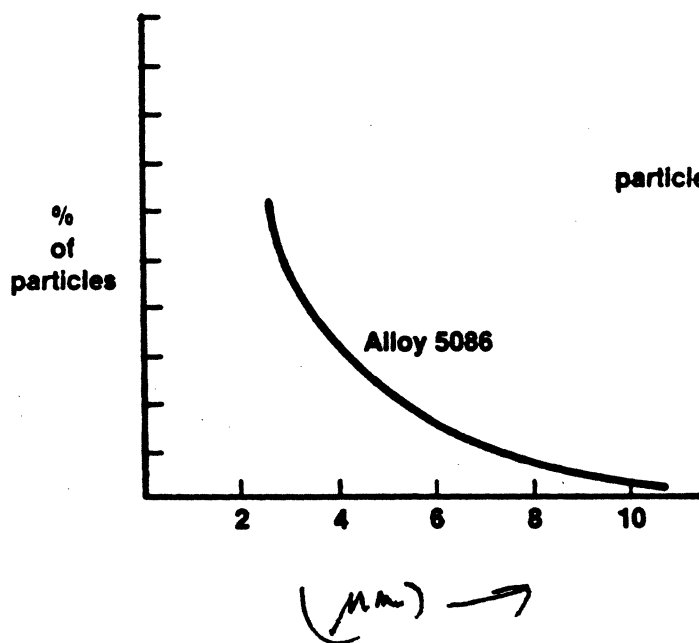
• noise

ref: Belk, George, and Mowry
J.A.P.

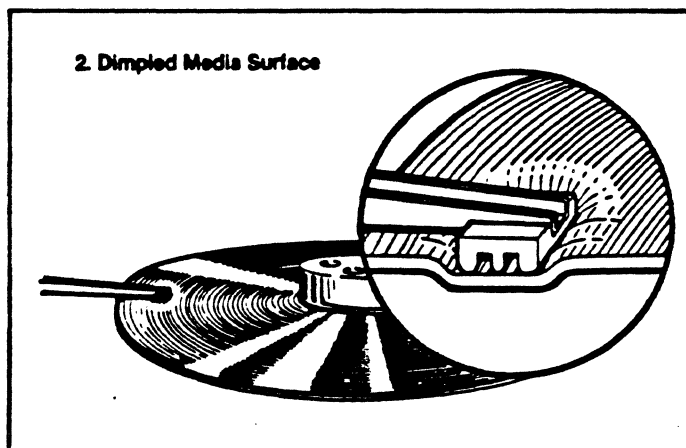
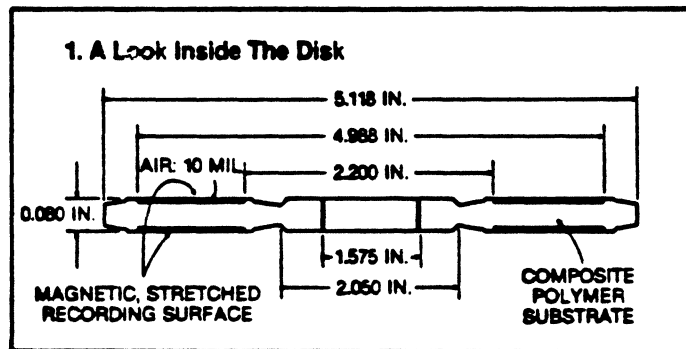
ALLOY 5086

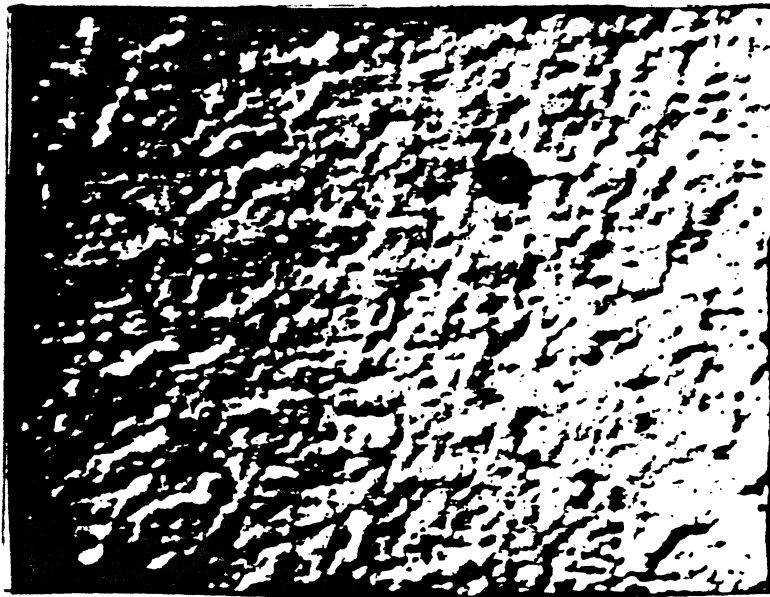
Composition

	Al	96%	
	Mg	4	
contaminants	Mn	— increase mechanical properties	
	Fe	} agglomerate ⇒ drop-ins drop-outs	
	Si		
	Cu		



STRETCH MEDIA - 3M



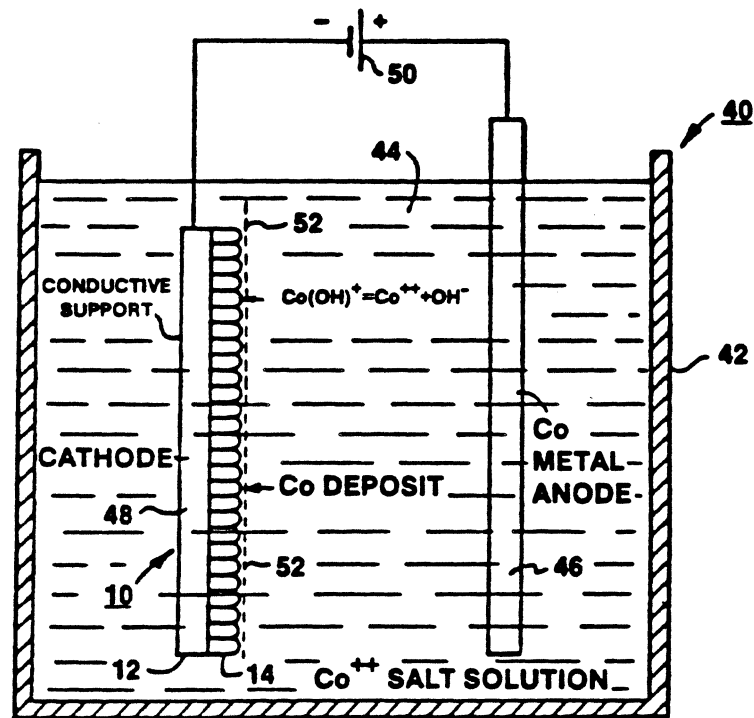


SURFACE OF A THICK (~ 25 MICRON)
Co FILM SHOWING NODULES



SCANNING ELECTRON MICROGRAPH OF A NODULE
APPROXIMATELY 22 MICRONS ACROSS

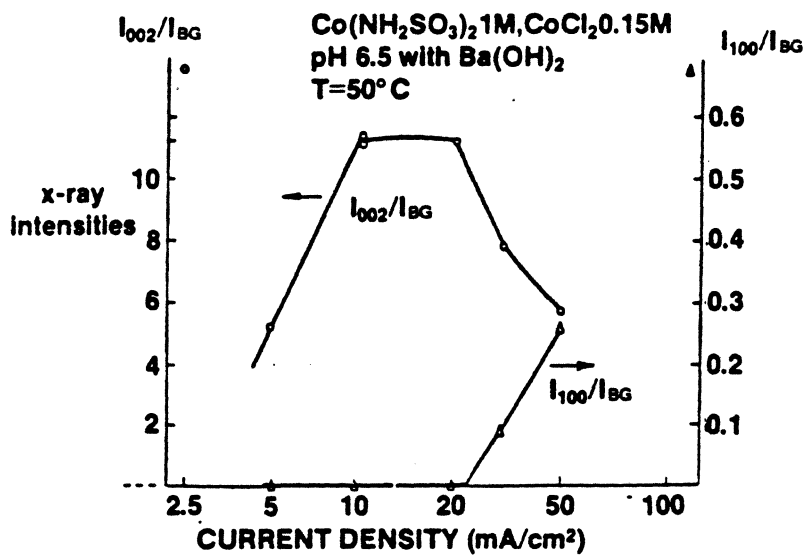
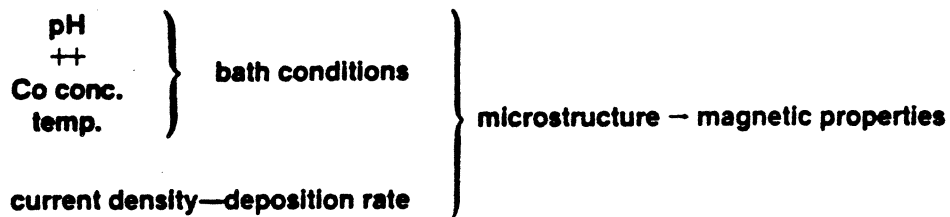
2. ELECTROPLATING



complexing reaction: Co(OH)^+ or $\text{Co}_4(\text{OH})_4^{4+}$
 ↓
 migrates to cathode

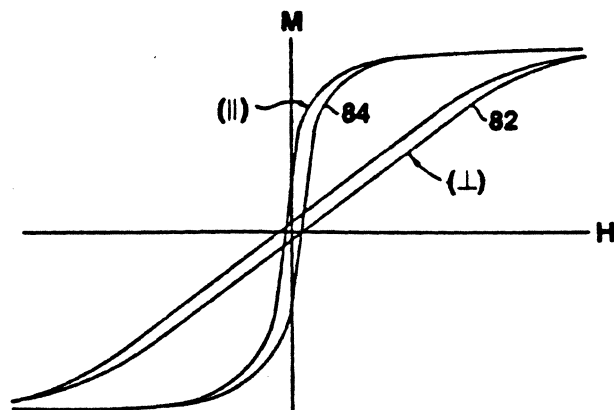
reduction reaction: $\text{Co(OH)}^+ + 2e^- \rightarrow \text{Co}^0 + (\text{OH})^-$

$\text{Co(OH)}^+ + (\text{OH})^- \rightarrow \text{Co(OH)}_2, \text{pH} \geq 7$
 ↓
 grain boundary

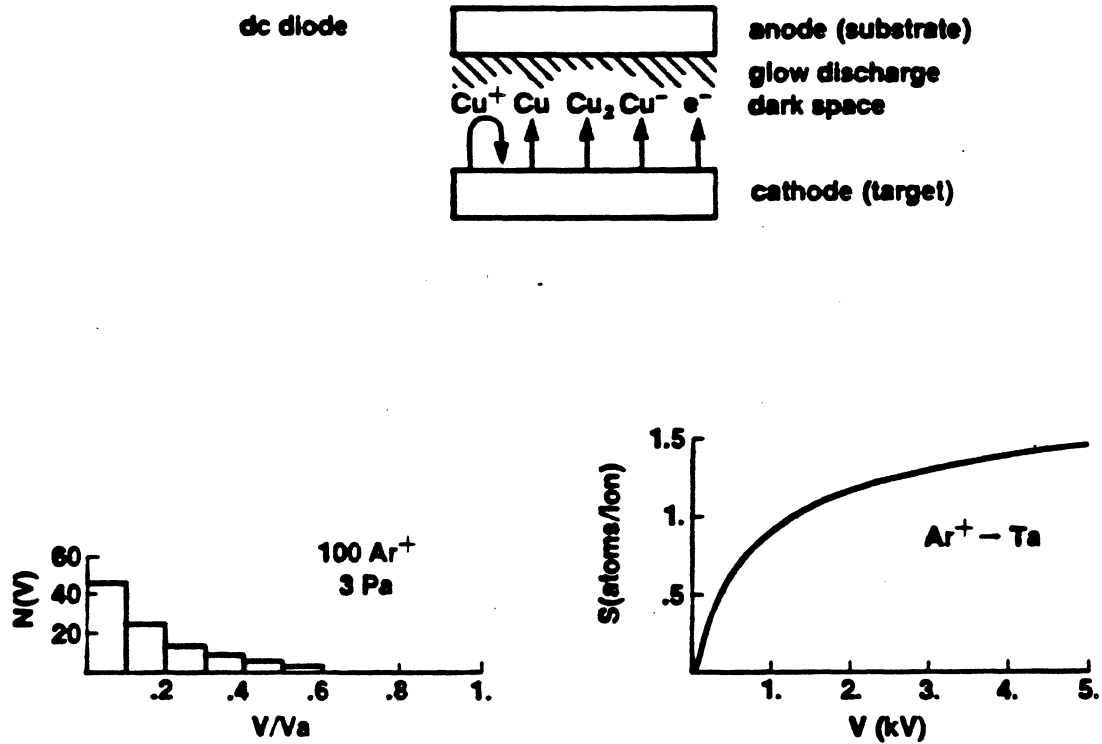


for random
 crystallites

{	I_{100}	1
	I_{002}	3
	I_{101}	5

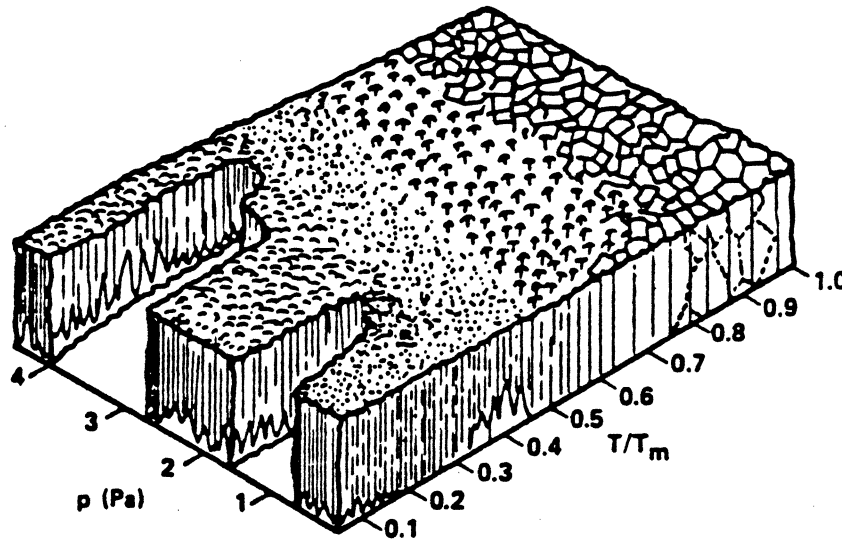


3. SPUTTERING



- Although ions may penetrate up to $500\text{\AA}$, sputtered atoms come only from top 2 or 3 atomic layers
- Ions incident at some angle to normal have higher yields
- Atoms with velocity normal to surface have greatest escape probability
- Sputtered atoms have energies of only a few eV for any incident energy

MORPHOLOGY



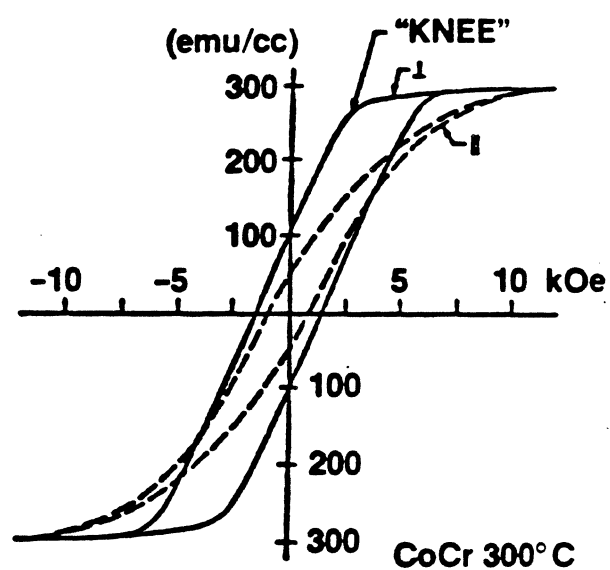
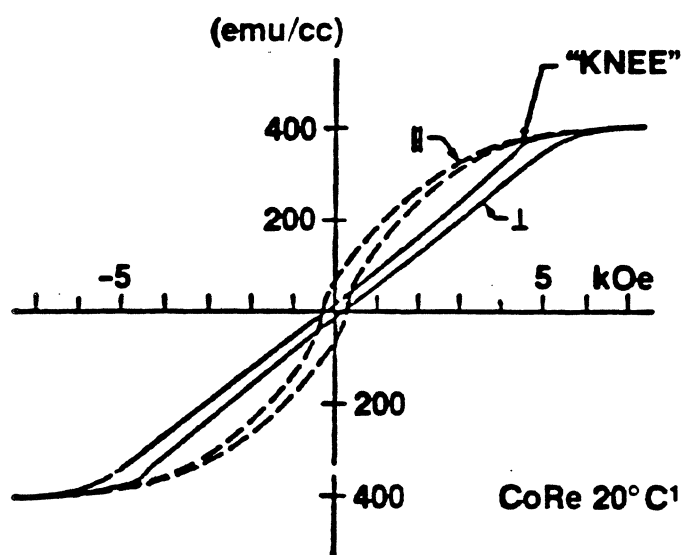
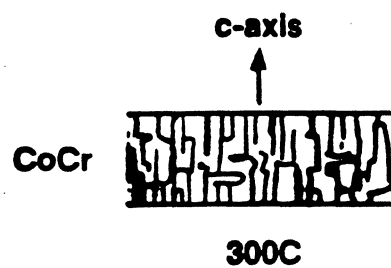
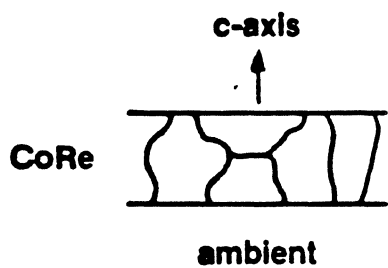
COMPOSITION

concentration of impurity $i = 6 \times 10^7 P_i S_i / R$

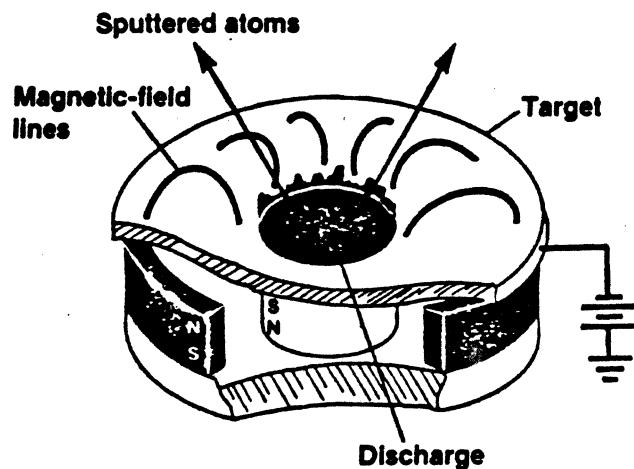
P_i = partial pressure

S_i = sticking coefficient

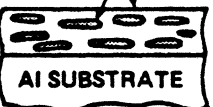
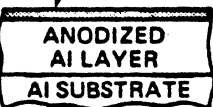
R = deposition rate ($\text{\AA}/\text{min}$)

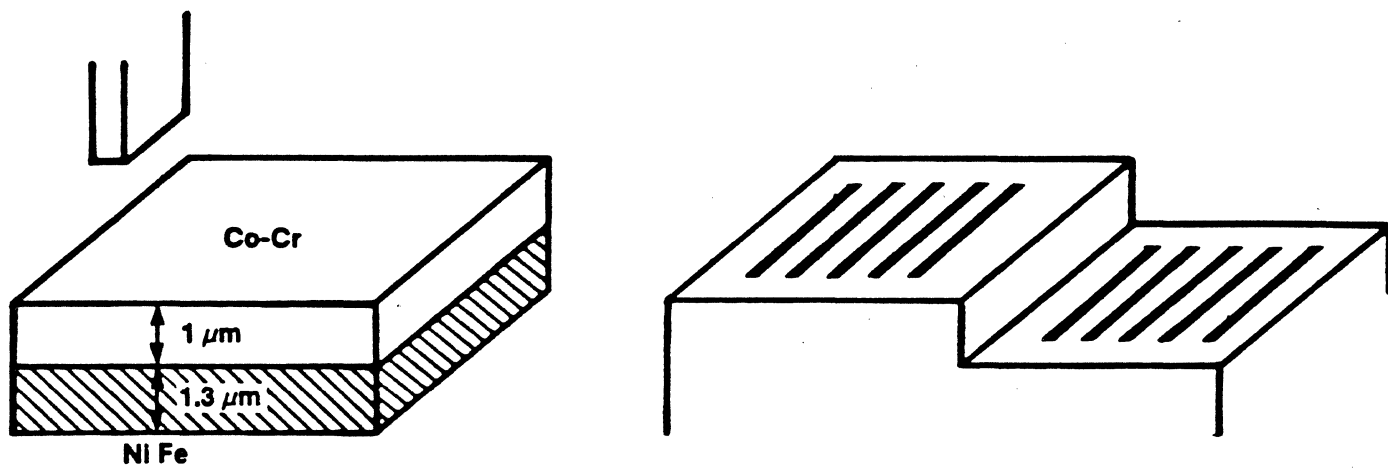
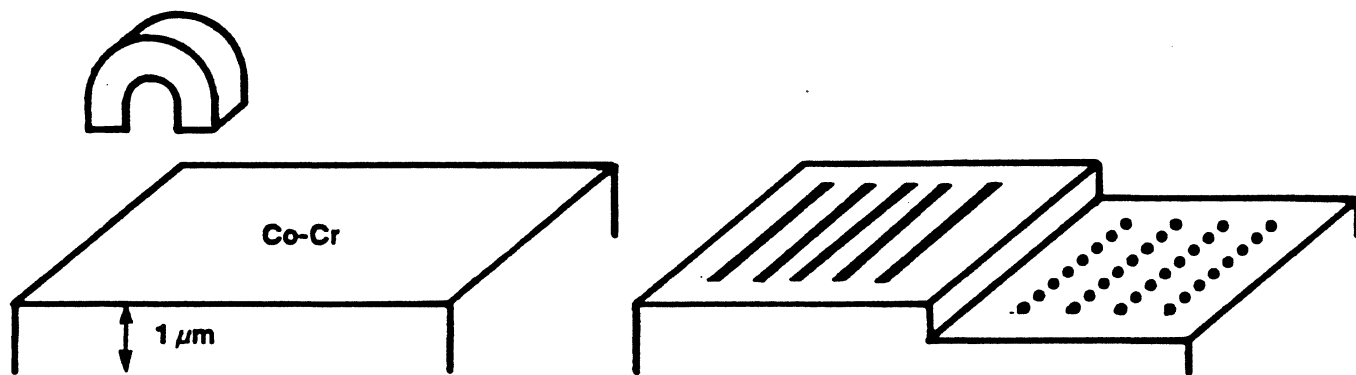


MAGNETRON SPUTTERING

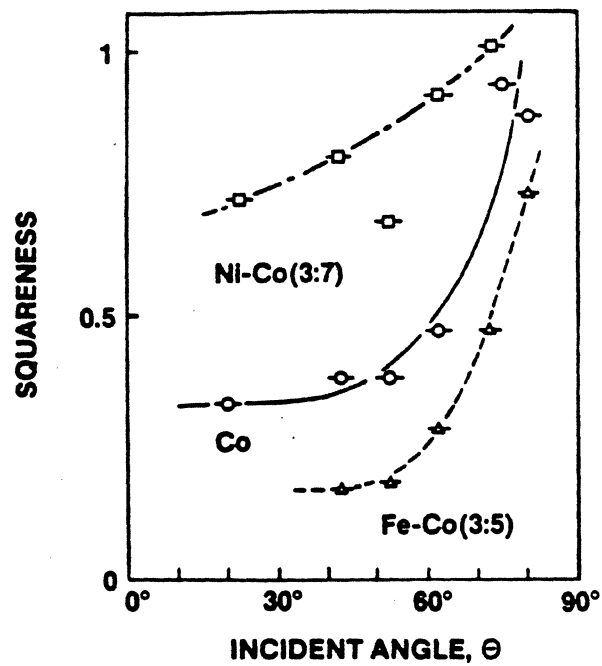
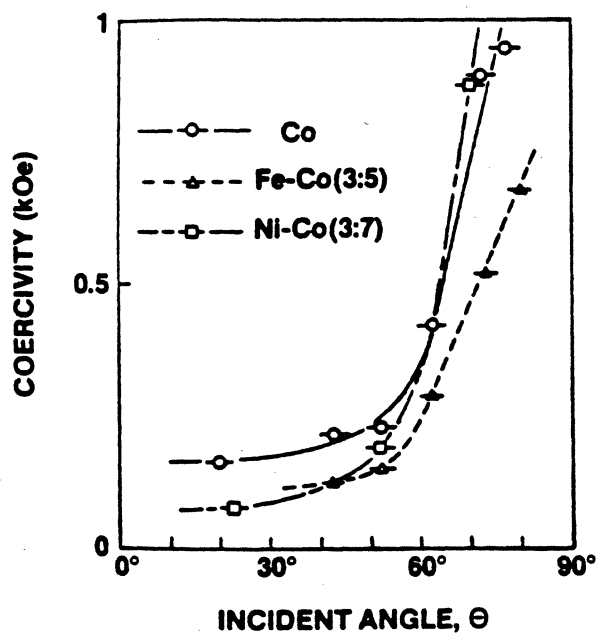
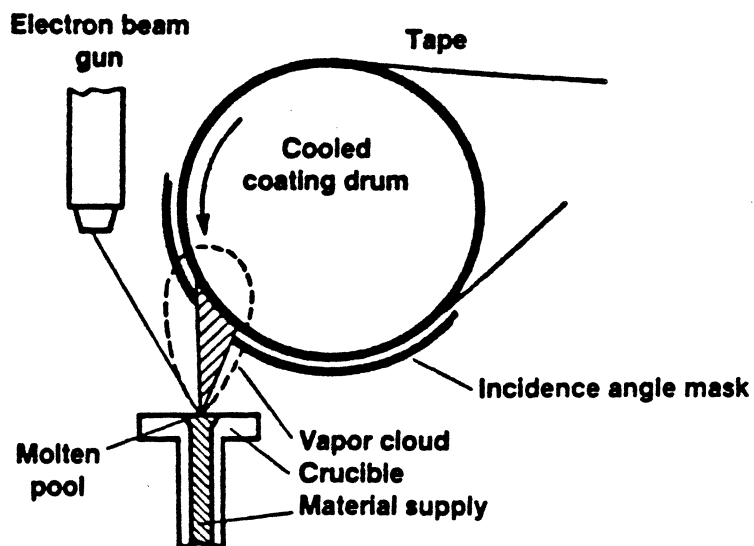


REACTIVE SPUTTERING

	COATED DISK	SPUTTERED FERRITE DISK
STRUCTURE	$\gamma\text{-Fe}_2\text{O}_3$ FINE PARTICLE  RESIN Al SUBSTRATE	$\gamma\text{-Fe}_2\text{O}_3$  ANODIZED Al LAYER Al SUBSTRATE
RECORDING DENSITY (BPI)	12,000	24,000
FILM THICKNESS (μm)	0.7	0.18
SURFACE ROUGHNESS (μm)	0.12	0.02
COERCIVE FORCE (Oe)	400	700



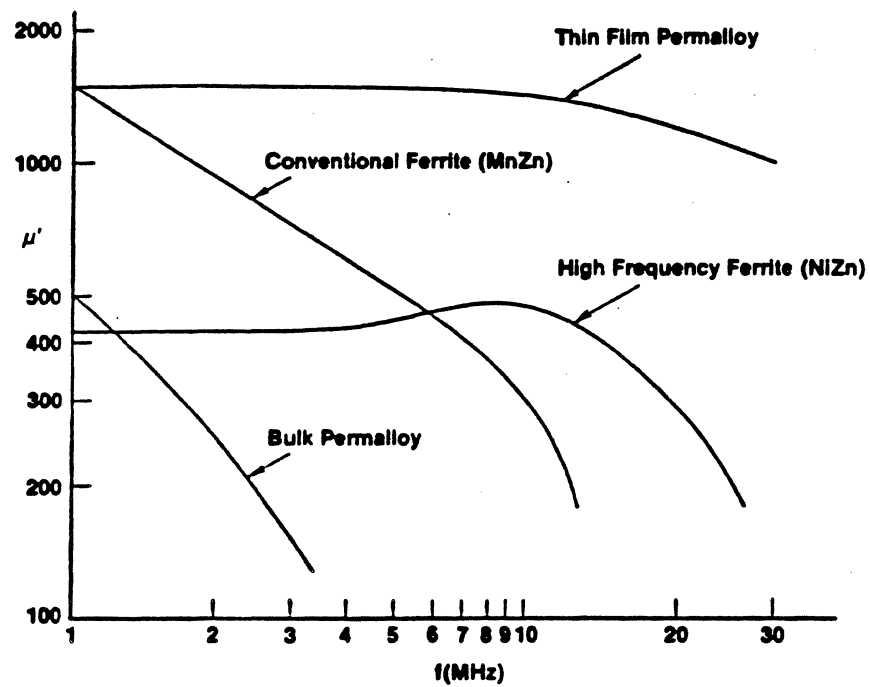
4. EVAPORATION



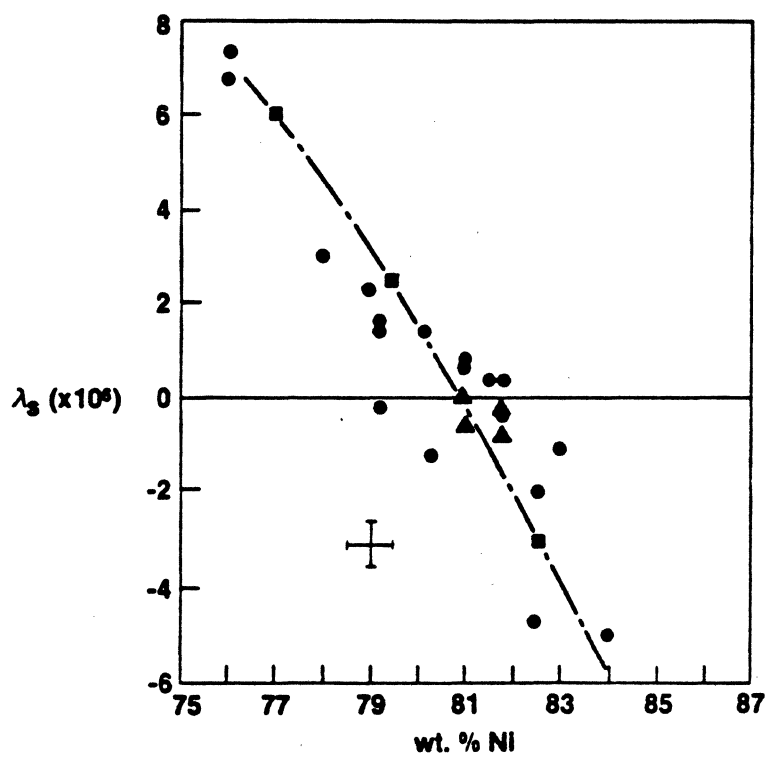
V. THIN FILM HEADS

ADVANTAGES

- Controlled dimensions
- Resolution enhancement
- Array potential
- Better frequency response



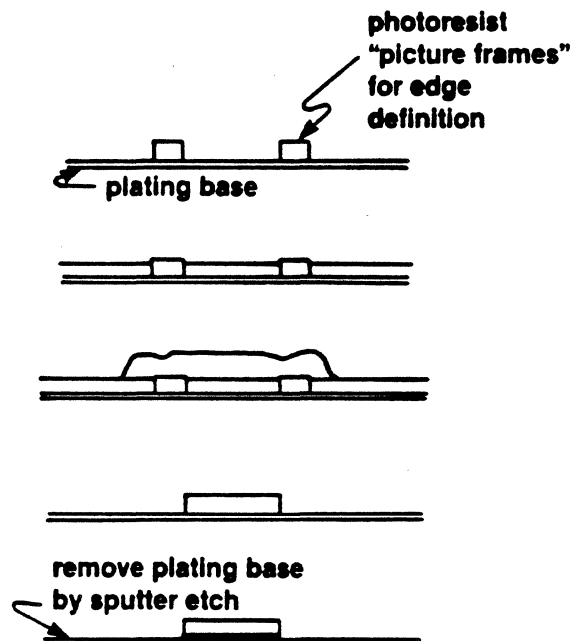
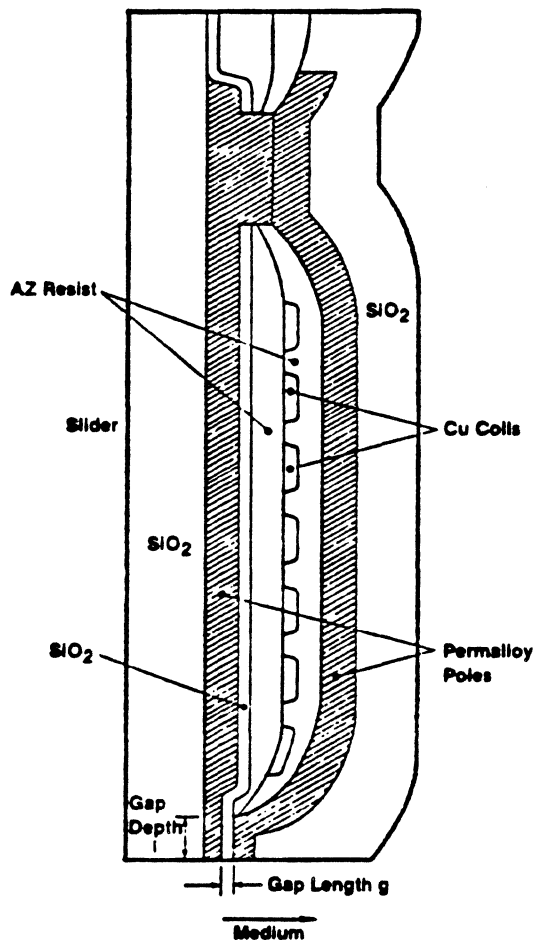
MAGNETOSTRICTION FOR Ni/Fe



THIN FILM HEAD FABRICATION

Substrate: polished oxidized si or ceramic ($\text{Al}_2\text{O}_3 + \text{tic}$)

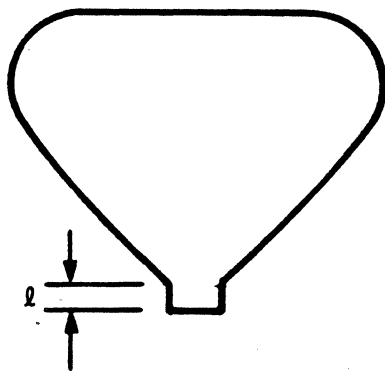
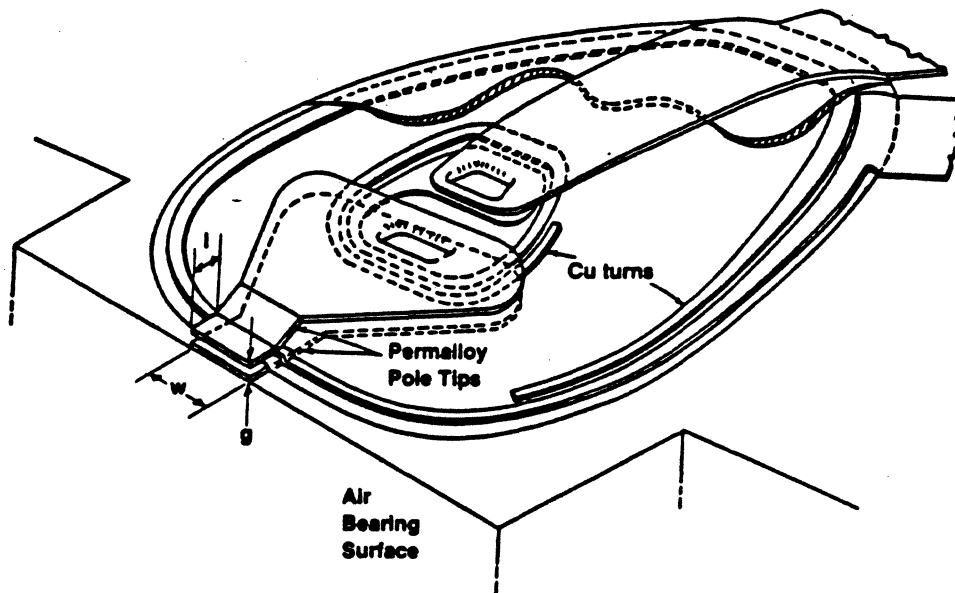
Permalloy: electroplated in 40 oe



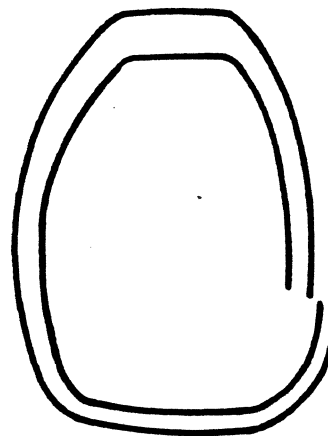
Gap: sputtered alumina

Colls: electroplate Cu thru photoresist mask
 thickness = $2\mu\text{m}$
 width = $3.5\mu\text{m}$ } 100 mA

Insulation: baked photoresist
 (provides smooth surface for top permalloy layer)

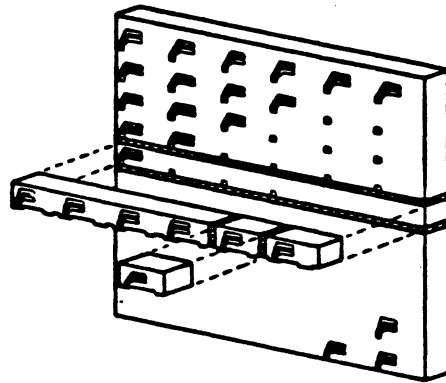


- $l \sim 5$ recording wavelength to reduce off-track reading
- yoke larger at back to avoid saturation



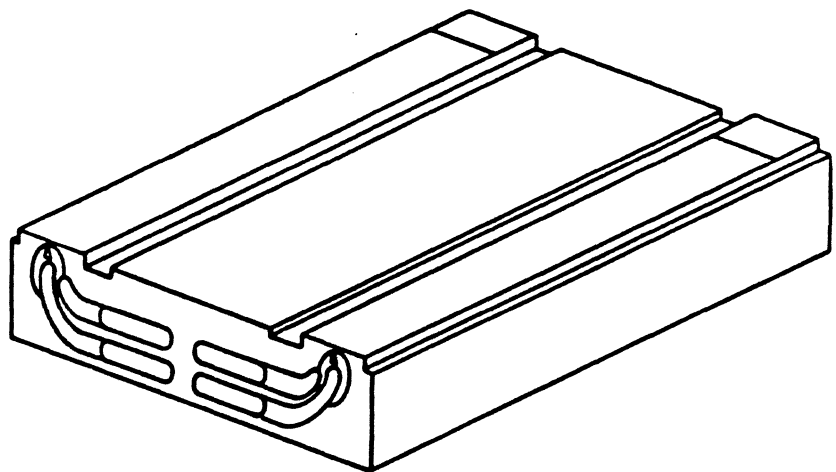
- elliptical coil with thicker conductors at back

cut into rows



**air bearing
surfaces
formed**

**sliders separated
and mounted on
suspension arms**

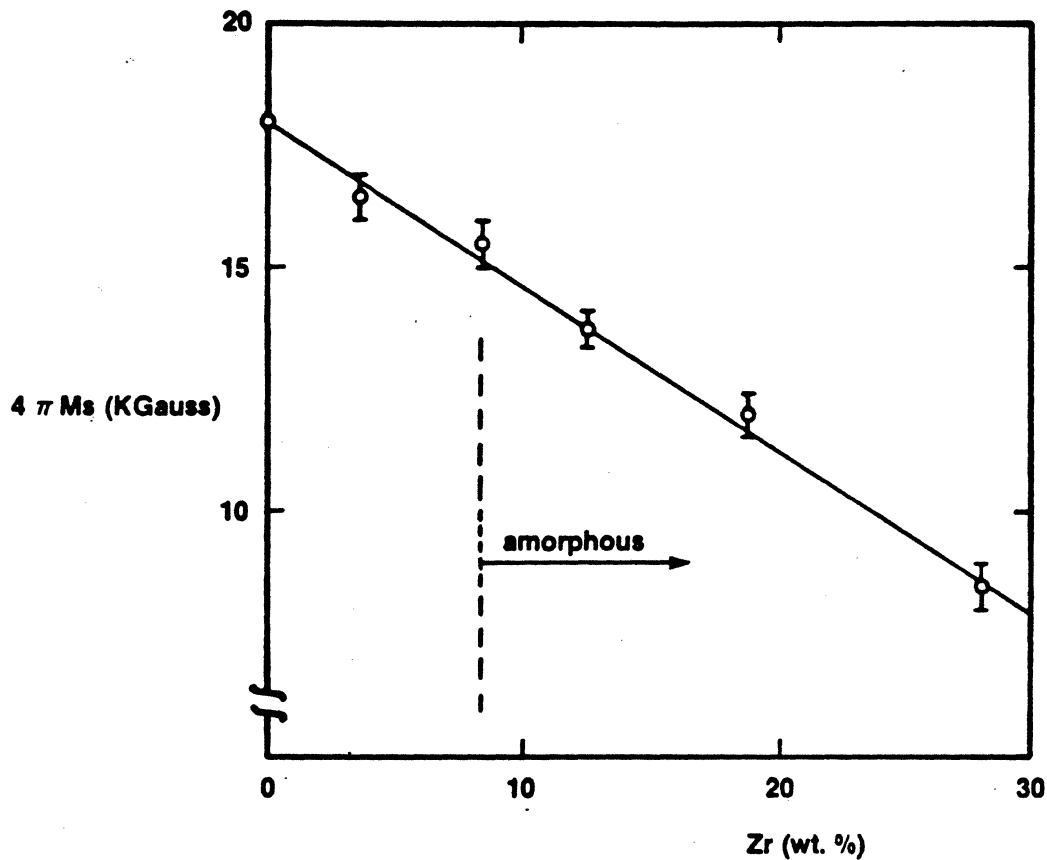


AMORPHOUS Co-Zr

Fabrication

Magnetron sputtering (600 Å/min)

Magnetic anneal (rotating 480 oe, 250 c, N₂, 2 hrs.)

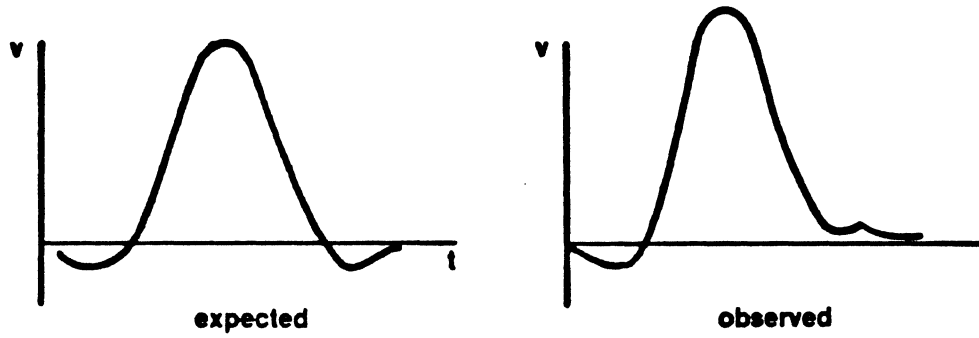


		4 π Ms (gauss)	H _C (or)
Ferrite	NiZn	3,300	0.5
	MnZn	5,000	0.05
Permalloy		8,300	0.02
Sendust (Al-Fe-Si)		10,500	0.02
a-Co-Zr		14,000	0.05

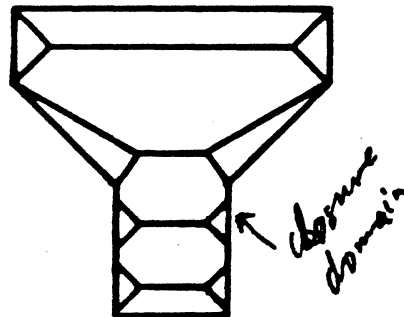
*magneticstriction
is not zero*

ASYMETRIC RESPONSE:

decrease the track width.



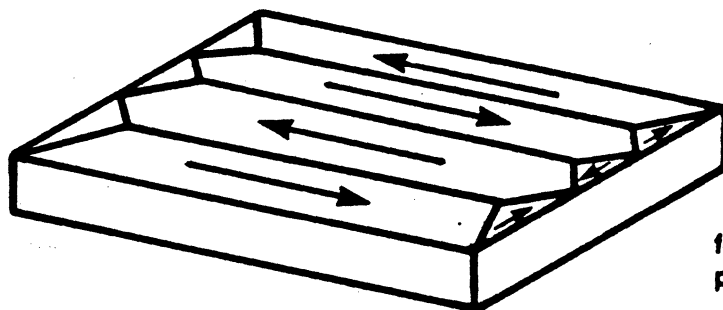
CLUE FROM BITTER PATTERNS:



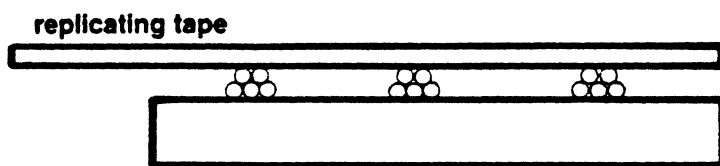
electroplated
Permalloy

$d \sim 1-2 \mu \Rightarrow$ Bloch
walls

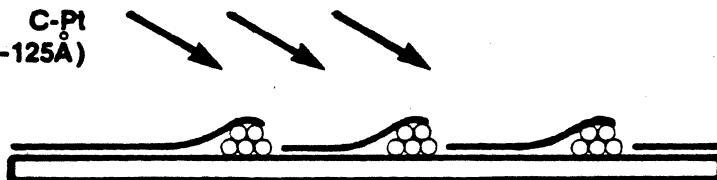
BITTER PATTERNS



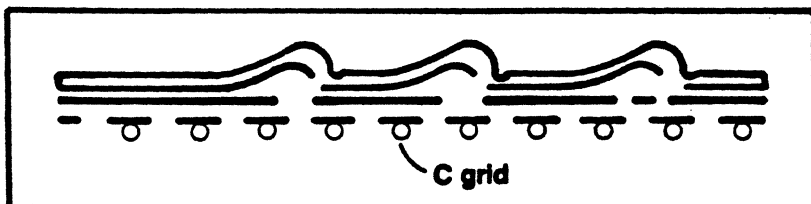
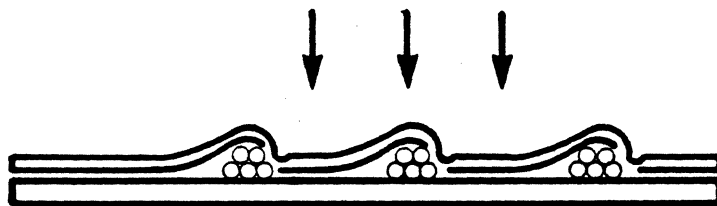
ferrofluid
particles $\sim 100\text{-}150\text{\AA}$



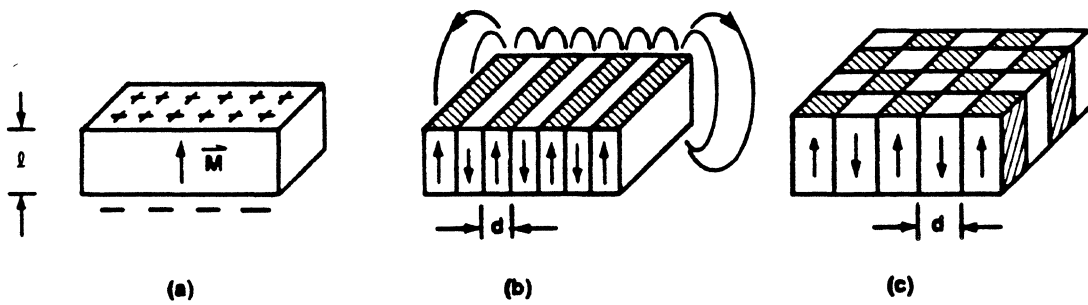
C-Pt
(80-125 $\text{\AA}$)



C (225-250 $\text{\AA}$)

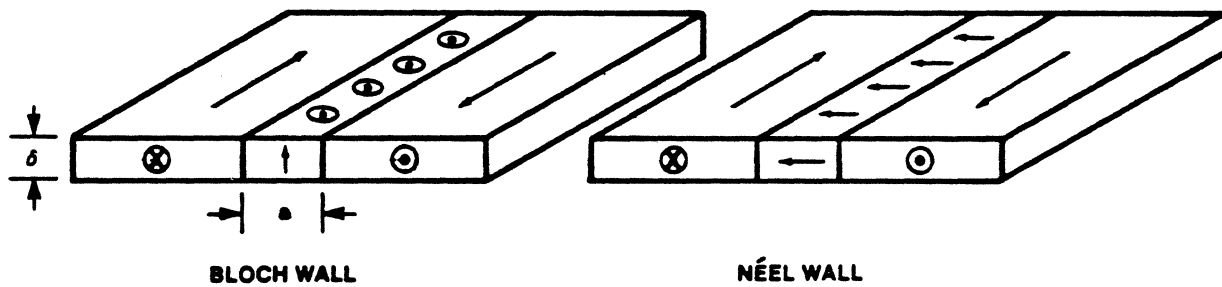


MAGNETIC DOMAINS

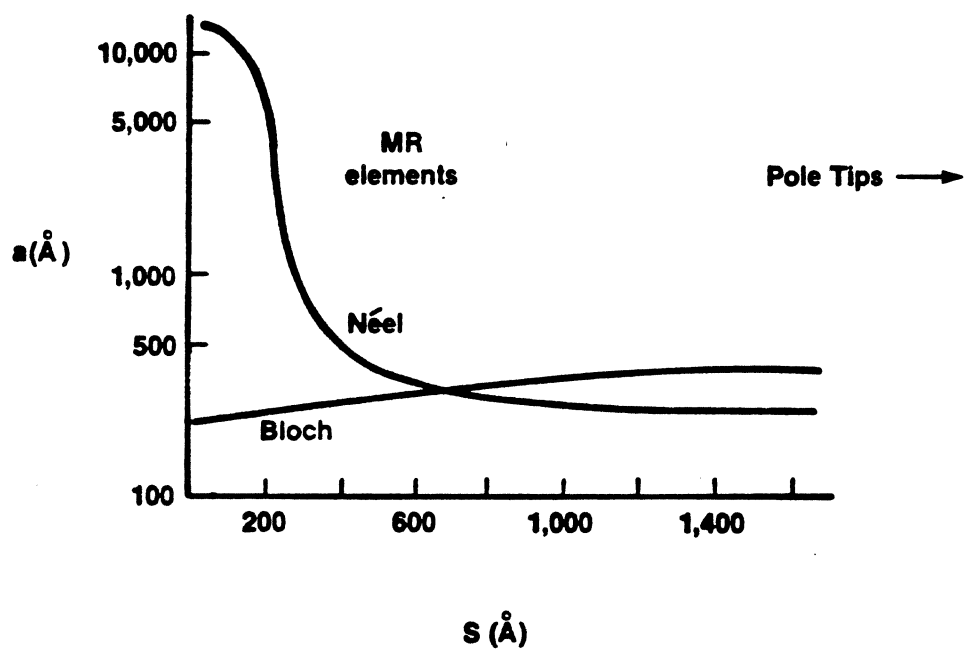
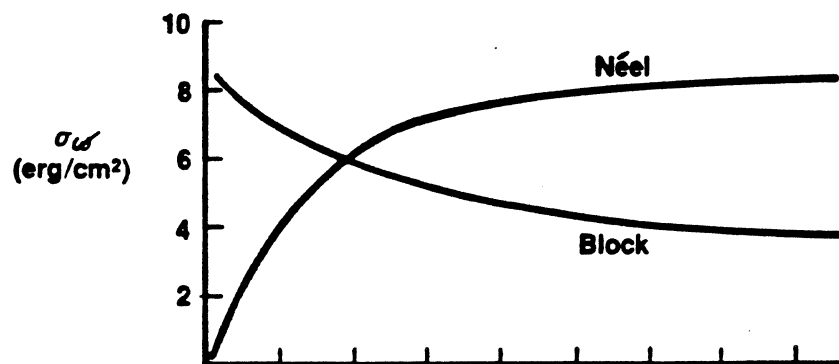


Magnetostatic energy (per cm ²)	$2\pi M^2 l$	$1.71 M^2 d$	$1.06 M^2 d$
Wall energy	—	$\sigma_w l/d$	$2\sigma_w l/d$

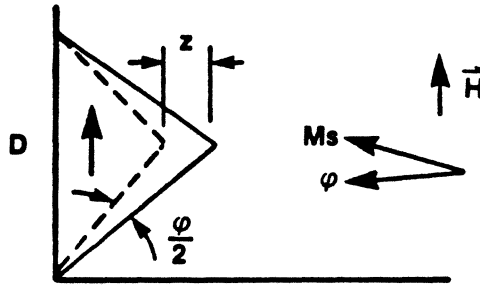
DOMAIN WALLS



			Permalloy	Co
Anisotropy energy	$Ka/2$	$Ka/2$	10^3	10^6 erg/cm^3
Exchange energy	$\pi^2 A/a$	$\pi^2 A/a$	10^{-6}	10^{-6} erg/cm
Demag	$\pi M^2 \left(\frac{a}{a+\delta} \right) a$ (surface)	$\pi M^2 \left(\frac{\delta}{a+\delta} \right) a$ (volume)	800	1400 gauss



SWITCHING BY DOMAIN WALL MOTION



$$\phi \approx \frac{H}{H_k}$$

$$z \sim \phi D/2$$

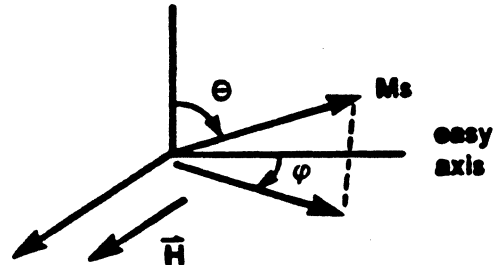
$$\beta \frac{dz}{dt} + \alpha z = \Delta (\vec{M} \cdot \vec{H}) \approx M_s H$$

↑
eddy current
damping

$$\beta = \frac{32 \delta M_s (4\pi M_s)}{\pi^2 c^2 \rho} \parallel$$

SWITCHING BY ROTATION

$$\frac{d\vec{M}}{dt} = -|\gamma| \vec{M} \times \vec{H}_{\text{eff}}$$



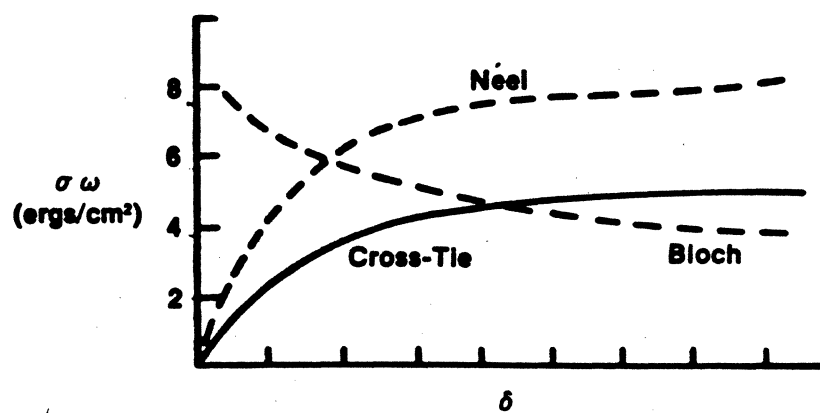
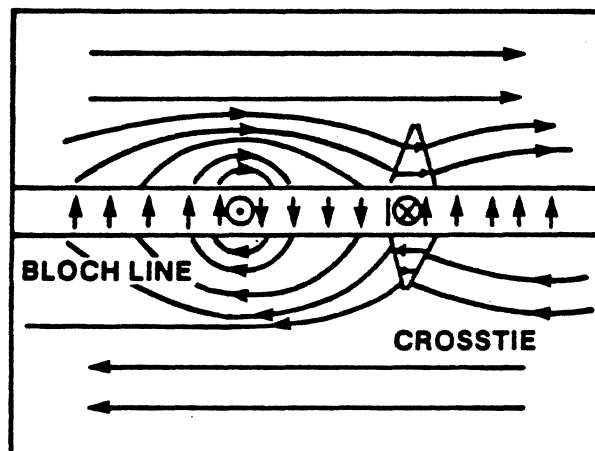
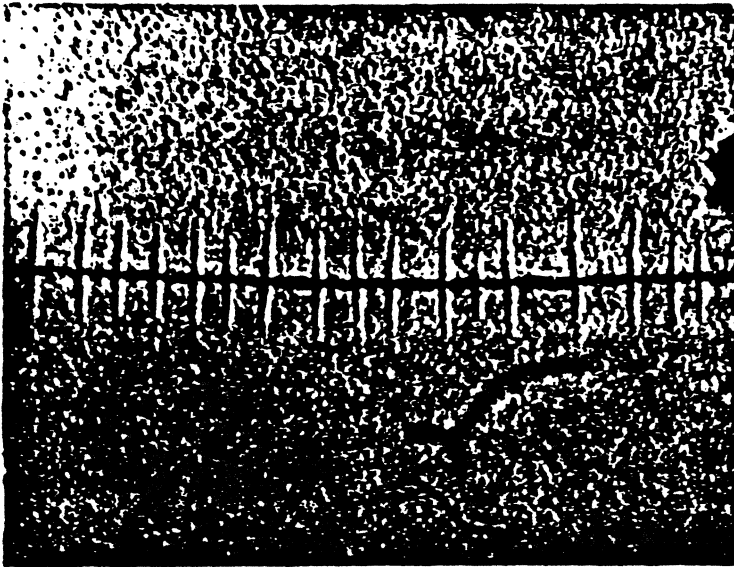
$$\vec{H}_{\text{eff}} = -\frac{\partial E}{\partial \vec{M}}$$

$$E = K \sin^2 \varphi - M_s H \sin \varphi$$

$$\left. \frac{d\vec{M}}{dt} \right|_{\text{relax}} = -\frac{\alpha}{|\vec{M}|} \vec{M} \times \frac{d\vec{M}}{dt}$$

$$M \dot{\theta} = -\frac{|\gamma|}{\sin \theta} [K \sin 2\varphi - MH \cos \varphi] + \alpha M \sin \theta \dot{\varphi}$$

$$\tau = \int_{\varphi_1}^{\varphi_2} \frac{d\varphi}{\dot{\varphi}} = \frac{\alpha M}{2MK} \ln \frac{1}{1 - \frac{\Delta \varphi}{n}} \quad h = \frac{H}{2K/M}$$



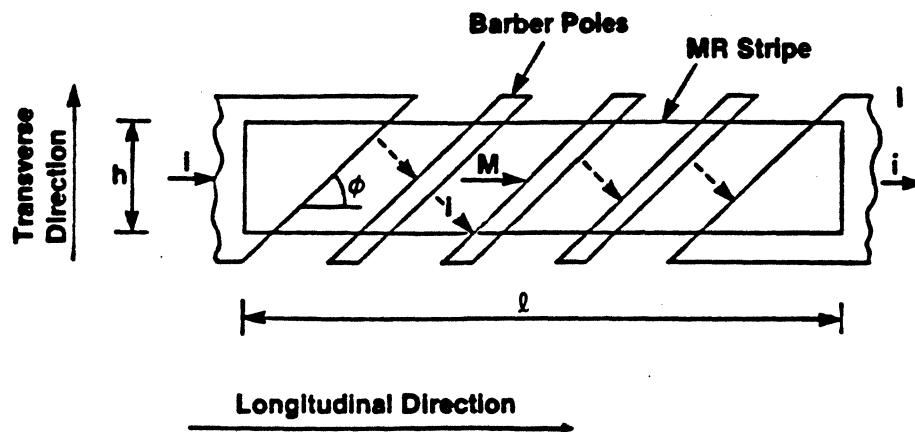
To reduce noise—establish single domain

- Reduce longitudinal demagnetization
 - Increase w/h
 - flux closure
- Apply bias
 - exchange

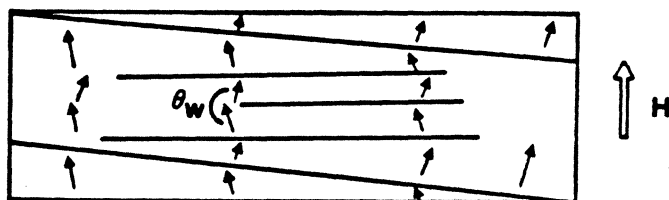
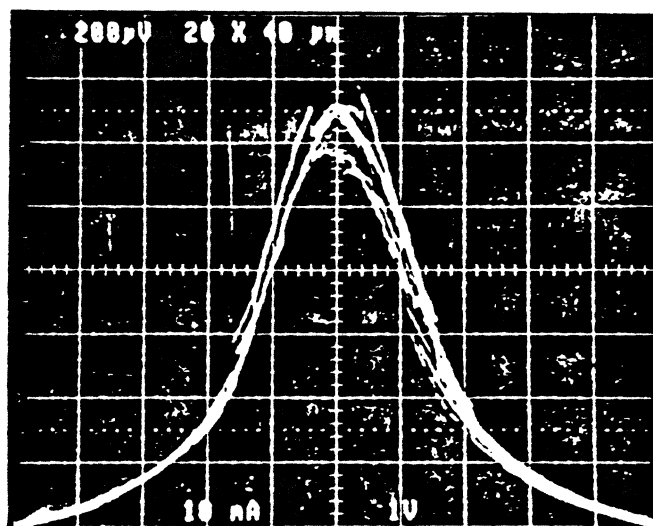
To linearize response—transverse bias

- Field biasing
- Current biasing

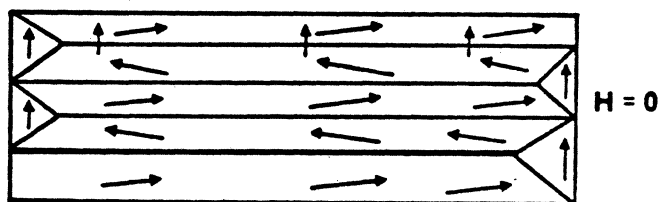
$$\rho \approx (\rho_{\perp} - \rho_{\parallel}) \left(\frac{H_c}{2K/M_s} \right)^2$$



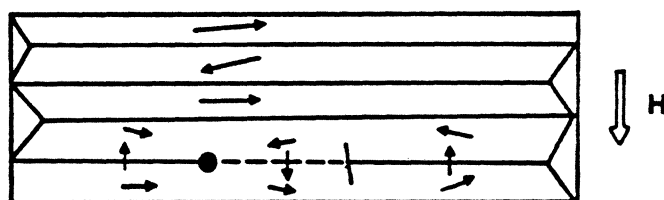
Barkhausen
noise



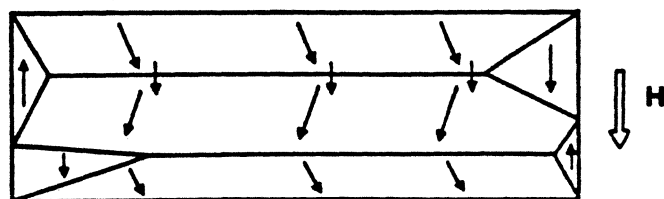
(a) Ripples at high field



(b) Well-defined buckling domain structure at low fields



(c) Onset of wall-state transition



(d) Closure pattern after $N^+ - N^-$ transitions

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0082/mm

Magnetic Recording Heads

Fred Jeffers
Kodak Research Laboratory

INTRODUCTION

This chapter outlines the important dimensions and parameters of high density heads and discusses why each is important and how they are related. Among factors discussed are: head to media contact, record gap size, media coercivity and remanence, record demagnetization fields, record and reproduce gap edge saturation in ferrite, metal, metal-in-gap and thin-film heads, and head wear. Gap edge straightness is discussed. Magneto-resistive read heads are described. Vertical recording and pole type heads are discussed. Principle sources of head noise are outlined.

SUMMARY

In order to achieve good high density performance, the heads and media must be in intimate contact. The record gap must be as small as possible but gap edge saturation must be avoided. In thin-film heads, yoke saturation must be avoided. This is made more difficult because high density media have high coercivity. The reproduce gap must be small enough to avoid gap loss but must be large enough that adequate signal is obtained with a gap depth providing adequate head life. Gap edges must be as straight and parallel as possible.

Vertical recording media give improved high density performance because the demag fields aid the record fields rather than oppose them, as in conventional media. Vertical pole heads work well in record but not in reproduce because of a trade-off in gap loss and efficiency. Ring-type heads offer superior reproduce performance with vertical media.

Magnetoresistive reproduce heads offer much higher signal levels than inductive heads, and they are easier to design to give tape noise limited signal to noise ratio.

Primary inductive head noise sources are resistance noise of the reproduce head, amplifier current noise which varies with net head impedance and amplifier voltage noise. Primary MR head noise is scrape thermal noise caused by hard asperities being dragged over the head surface. The goal in a properly designed system is to make the sum of these noises smaller than the media noise.

The intent of this paper is to outline why the above statements are true and provide understanding and a semi-quantitative basis for making design optimization trade-offs.

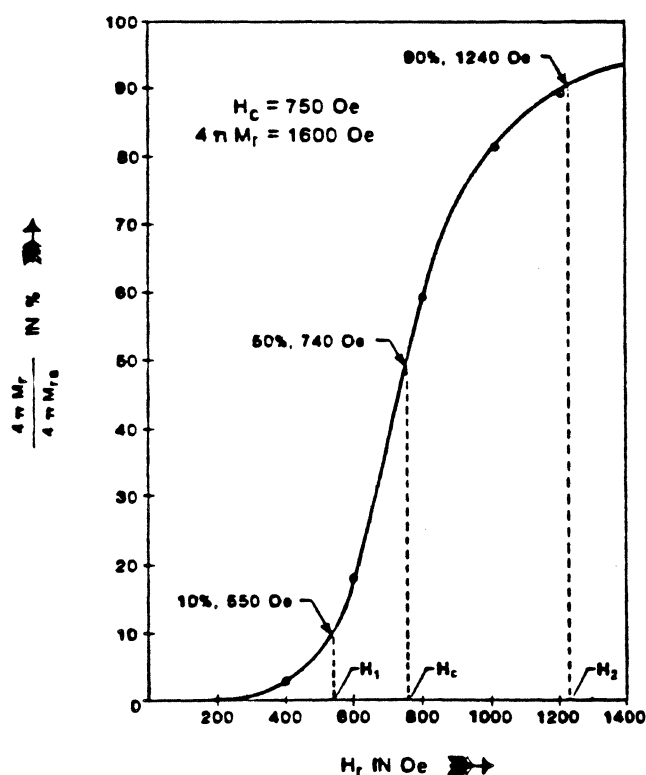
DISCUSSION

Recording Process

In high density recording, nearly all of the reproduce signal comes from the surface of the medium. If $B \ell$ is the bit length, 90% comes from the top $0.74 B \ell$ of the surface. At 100 KBPI, $B \ell = 0.25 \mu$, so $0.74 B \ell = 0.19 \mu$. Essentially only the top layer of particles is recorded at high density.

If a signal field H is applied and removed, neglecting demagnetization fields, the medium is magnetized according to the curve sketched in Figure 1 where $4\pi M_r$ is the remanence and $4\pi M_{rs}$ is the saturation remanence.

FIG. 1 REMANENCE VERSUS RECORD FIELD



H_1 and H_2 define the boundaries of the record field range and the 50% field is generally close to the media coercivity H_c .

FIG. 2a MAGNETIC HEAD

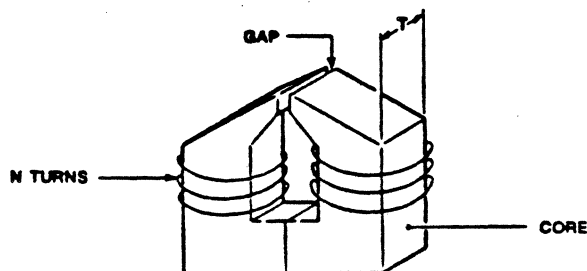
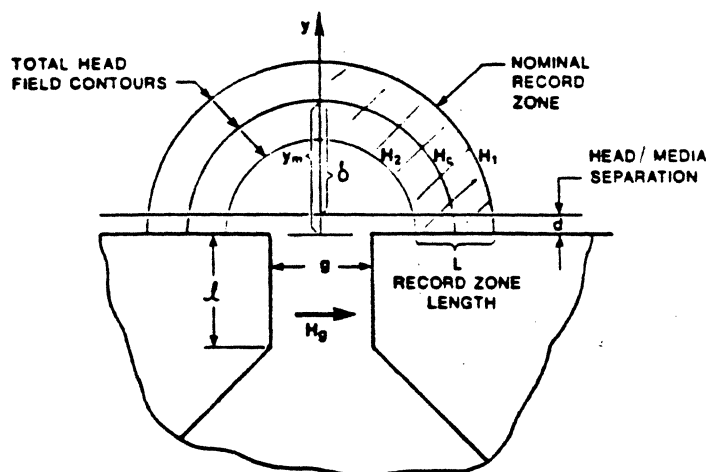


FIG. 2b CROSSECTION OF RECORD GAP & HEAD FIELD CONTOURS


$$H_g = E \frac{4 \pi N i_r}{10 g} \quad (1)$$

H_g in Oe
 i_r in amp.
 g in cm.

where E is the head efficiency. E represents that fraction of the magnetomotive force Ni_r that appears across the gap. (It is also the fraction of the tape flux passing through the coils during reproduce.) McKnight¹ gives a good review of detailed efficiency calculations for standard heads. Neglecting "air leakage," E is given approximately by

$$E = \frac{R_g}{R_g + R_c} \quad (2)$$

where R_g is the gap reluctance given by

$$R_g = \frac{g}{T \ell} \quad (3)$$

where g is the gap length, T is the track width and ℓ is the gap depth. The core reluctance R_c is given by

$$R_c = \frac{C}{\mu \bar{A}} \quad (4)$$

where μ is the core permeability and C is the circumference of the core. $\bar{A}$ represents the "average cross sectional area" of the core. Care must be taken to be sure that the fabrication process does not reduce the permeability of the head core material by inducing strain. Reduction of a factor of 5 is not uncommon.

At high density, when the bit length approaches half the record zone length $L/2$, the high H_c fraction of the particles in the medium are recorded "positive" and the low H_c fraction are recorded "negative" as sketched in Figure 3.

1. J. McKnight, Jour. Audio Eng. Soc., Vol. 27 #3, March 1979, pg. 106.

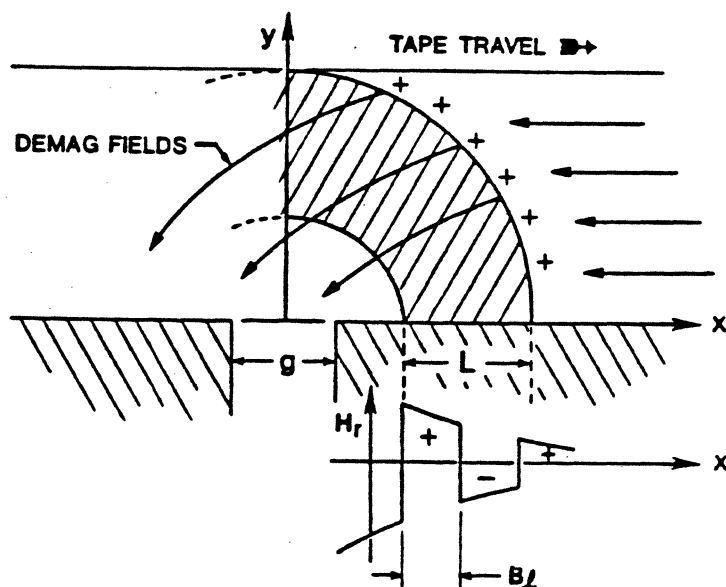


FIG. 3 High density record field versus distance compared to a long record zone length.

This results in cancellation and hence a low recorded signal. This is called subsequent cycle erasure or recording demagnetization.

When the head-tape separation d increases, L , at the surface of the medium, increases giving more erasure at high density. Bertram² has shown that for standard high density media having $4\pi M_r s/H_c$ ratios ≈ 3 , the record separation loss is given by $-44 d/\lambda$ dB where λ is the fundamental wavelength or twice the bit length B_L . This expression is a conservative estimate of the loss caused by a momentary loss of contact, such as that due to a speck of dirt on the medium, because in Bertram's experiment, the record current was increased to partially compensate for the loss of contact. If H_c is increased, this loss factor becomes smaller because the record fields then become larger relative to the demag fields and less recording demagnetization occurs.

The reproduce separation loss is the familiar³ $-55 d/\lambda$ dB so the net separation loss is about $-99/\lambda$. If d is $\lambda/10$ the signal loss is 9.9 dB or about a factor of 3. If the recording density is 100 KFCI, $\lambda/10 = 0.05\mu$ or about 250 air molecules lined up in a row! The importance of good head to media contact cannot be over emphasized!

2. N. Bertram IEEE Trans. on Mag., Vol. Mag 18, No. 6, Nov 1982, pg. 1206.
3. R. Wallace, Bell Tech. Jour., Oct. 1951, pg. 1145.

The standard approach to achieving a narrow record zone is to use a small record gap. It has been shown that for any bit length less than the medium thickness, when the head and medium are in good contact, the maximum recordable signal increases as the record gap is reduced and reaches a maximum when saturation occurs at the gap corners.⁴ Figure 4 shows the maximum unbiased RMS signal versus frequency at a constant tape speed of 19.1 cm/sec for 3 metal tipped record heads having gap lengths of 1.9 μ , 0.86 μ , and 0.25 μ . The heads have ferrite cores and "glued on" Sendust pole tips as sketched in Figure 5. The same reproduce head having a gap of 0.25 μ was used for each curve. The media was an acicular Co doped $\gamma\text{Fe}_2\text{O}_3$ tape with $4\pi M_r \approx 1500$ G and $H \approx 860$ Oe. The record current was optimized at each frequency. The highest frequency of 300 KHz corresponds to 80 KFCI digital density. The very small 0.25 μ gap head records 10 dB, or a factor of 3, more 80 KFCI signal than does the 1.9 μ gap head.

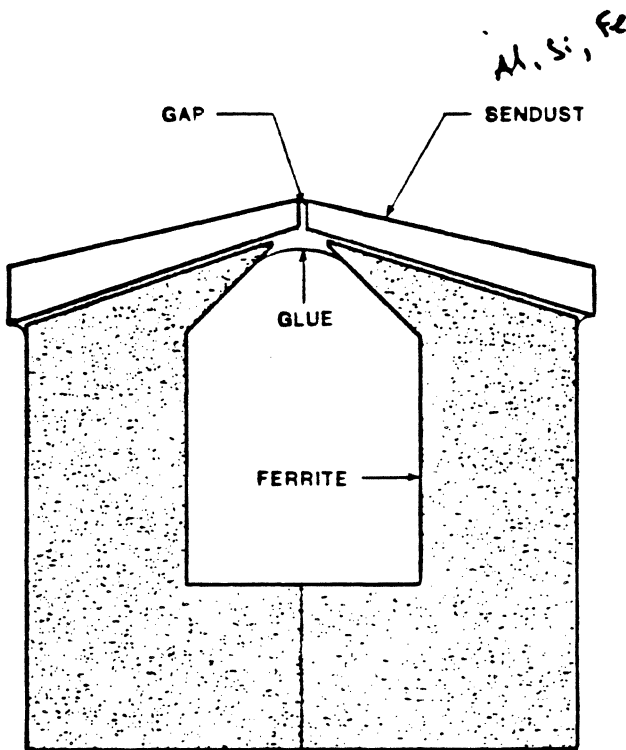


FIG. 4 SENDUST TIPPED HEAD CROSSECTION.

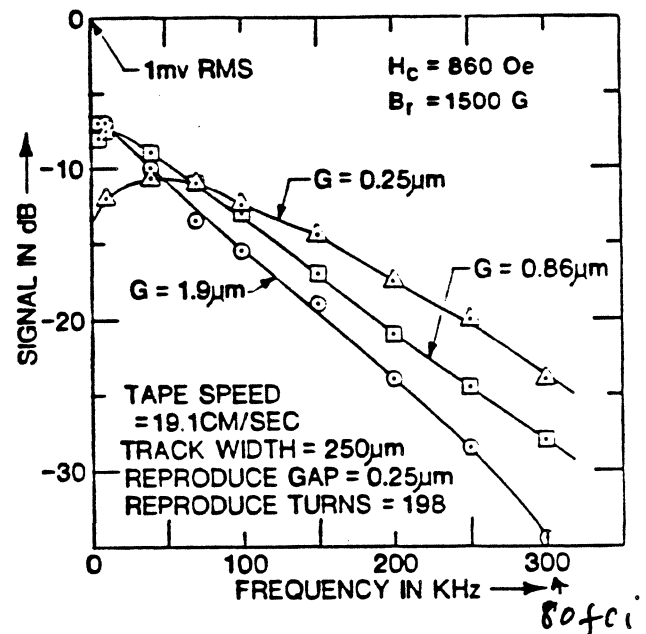
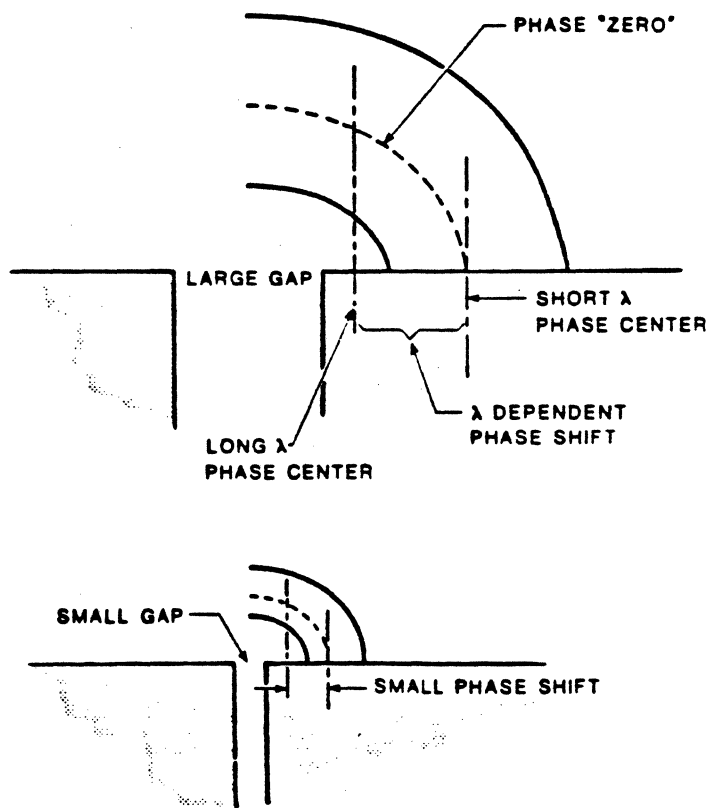


FIG. 5 Record performance of three different Sendust tipped record heads gaps.

4. F. Jeffers, IEEE Trans. on Mag., Vol. Mag. 18, No. 6, Nov. 1982, pg. 1146.

Smaller gap record heads also give less record phase shift because the record zone has less curvature and what curvature there is has a smaller radius, - i.e., the recording occurs closer to the gap. See Figure 6. For applications such as disk storage devices, where no erasure takes place, but old data is simply overwritten, Lemke⁵ has shown that excellent overwrite of 30 dB can be obtained using 0.25μ record gaps at a density as high as 120 KFCI. Recent work has shown that optimum overwrite is obtained when $g \approx \lambda/2$.⁶

FIG. 6 WAVELENGTH DEPENDENT PHASE SHIFT
FOR LARGE AND SMALL RECORD GAPS.



5. J. Lemke, IEEE Trans. on Mag., Vol. Mag: 15, No. 6, 1979, pg. 1561.
6. D. Wachenschwanz and F. Jeffers to be published in 1985 Intermag Proc. Digest in notes.

In addition to the head fields acting on the medium, when the head and medium are not in "perfect" contact, there are also demagnetization fields arising from the media itself. In conventional media, these "demag" fields tend to oppose the head record fields and thus smear-out or increase the length of the record zone, hence, reducing recorded signal. They also lead to "non-linear bit shift" where the location of a recorded transition is influenced by the demag field of the preceeding bit or string of bits. The demag fields are limited to $4\pi M_r$, while the record fields are proportional to H_c . Increasing H_c requires a proportional increase in the record field, and the demag fields then have less effect on the record zone, which allows more signal to be recorded and minimizes non-linear bit shift. Increasing H_c also reduces the slope of the record separation loss for the same reason.

Gap Corner Saturation

Unfortunately, making record gaps smaller and coercivity higher, in an effort to achieve more signal and less non linear bit shift at high density, requires higher gap fields to do the recording. In typical high permeability ferrites, like MnZn ferrite, when the gap field exceeds about half the saturation flux density $4\pi M_s$, the corners of the gap become saturated. This causes the record zone to become longer and loss of signal results. Hence gap edge saturation sets a lower limit on the record gap length.

Eq. 5 below relates the gap field H_g required to record maximum level signals of wavelength λ on a medium of coercivity H_c using a head of gap g where λ and g are in μm . Good head to media contact is assumed.

$$H_g \simeq \left(\frac{1.7}{g^{0.33}} + \frac{0.8\lambda}{g^{0.78}} \right) H_c \quad (5)$$

λ, g in μm

This field is very nearly the same as the bias field in ac bias recording so the conclusions apply there, as well as in unbiased recording.

Equation 5 was obtained using record currents and other data obtained in generating the curves in Figure 4 and similar curves using tapes of different H_c . It is an analytic fit to the data.

The apparent maximum in the $g = 0.25\mu$ curve at about 70 KHz in Figure 4 is due to saturation in the Sendust pole tips of the record head. The saturation flux density of Sendust is about 9500 G and Eq. 5 gives $H_g = 7800$ Oe for $\lambda = 2.73\mu$, $g = 0.25\mu$ and $H_c = 860$ Oe. This gap field is 82% of saturation and causes gap edge saturation.

Eq. 5 can be used to determine if a head design will suffer from saturation effects. For ferrites, if H_g is much larger than about $0.5 (4\pi M_s)$, saturation is occurring and a larger gap or a higher $4\pi M_s$ head material should be used.

Figure 7 shows the gap field above a ferrite audio head, measured with an SEM, plotted versus record current.⁷ Clearly saturation is important at $H_g \geq \frac{4\pi M_s}{2} \approx 2000$ Oe.

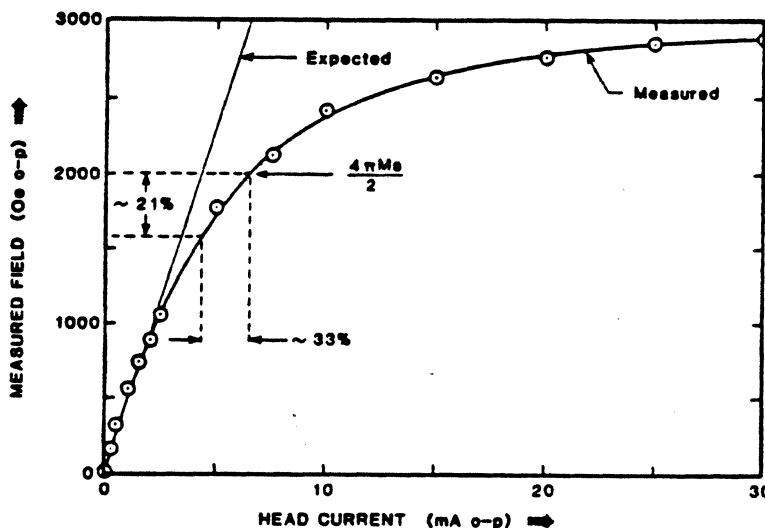


FIG. 7 FIELD VERSUS CURRENT FOR A $5 \mu\text{m}$ GAP FERRITE AUDIO CASSETTE HEAD.

Figure 8 shows the comparative 80 KFCI signal recorded on a 1350 Oe coercivity metal particle tape by a Sendust tipped head, a MIG head (discussed below) and a ferrite head, plotted versus record current. The ferrite head signal is 8.5 dB below that recorded by the Sendust tipped head even though both have the same $0.3 \mu\text{m}$ gap.

7. R. Camorata and D. Thompson presented at 1983 AIP Magn. & Mag. Mtls. Conf. in Pittsburgh

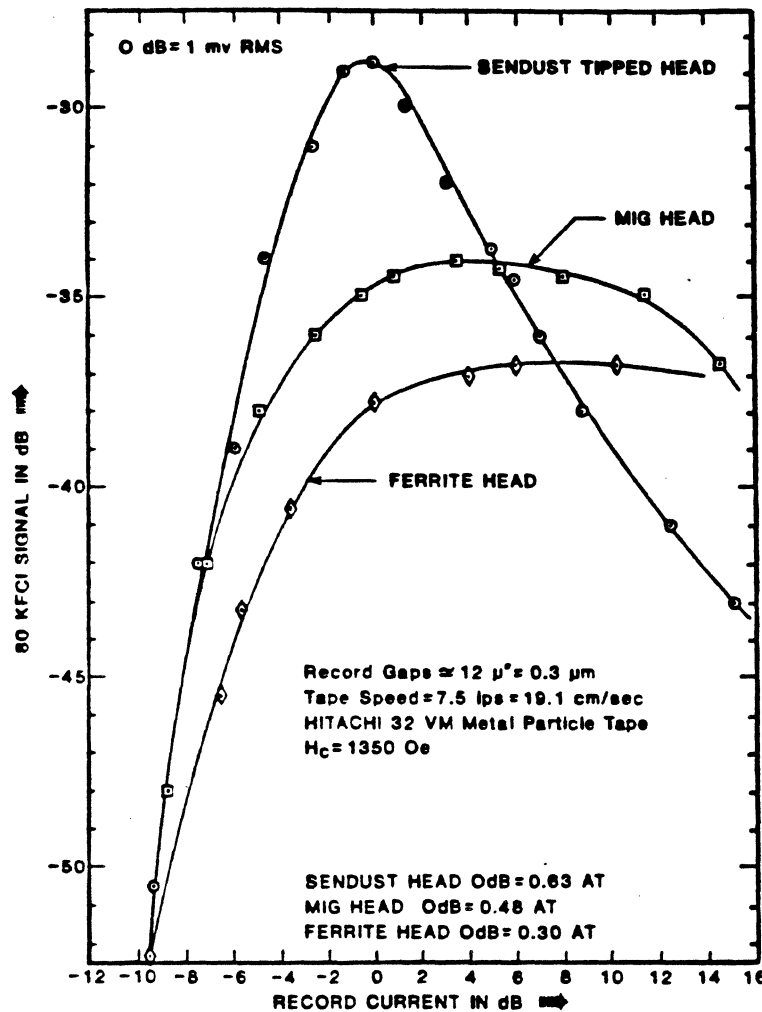


FIG. 8 80 KFCI SIGNAL RECORDED ON $H_c = 1350 \text{ Oe}$ METAL PARTICLE TAPE BY SENDUST, MIG AND Mn Zn FERRITE HEADS VERSUS RECORD CURRENT.

Up to now, we have ignored the coercivity of the core, H_c (core), which can be as low as 0.05 Oe for well annealed MnZn ferrite. If the head is exposed to some sort of dc transient which saturates the core, the field in the gap which results can be large if the gap length is as small as 0.25μ . H_g (core) is given roughly by

$$H_g (\text{Core}) \approx H_c (\text{Core}) \frac{c}{g} \quad (6)$$

airman pencil

where C is the core circumference. Using $H_c = 0.05$ Oe and $C = 1$ cm with $g = 0.25 \times 10^{-4}$ cm we have H_g (core) = 2000 Oe, which is more than half the 80 KFCI record field for an 800 Oe coercivity tape! This dc gap field will result in considerable second harmonic distortion and signal loss. A dc gap field of only 200 Oe will give enough second harmonic distortion to produce significant high density peak shift and poor measured 1F/2F overwrite. Recording heads should always be "degaussed" prior to use. Commercial hand-held units are available or a "ring down/up" circuit can be built into the drive electronics.

For systems where the record head must also serve as the reproduce head, the maximum gap is limited to no more than about $\lambda/2.5$ because of the "gap loss term,"¹⁸ $\sin(X)/X$, $X = 1.14\pi g/\lambda$. Even for $g = \lambda/2.5$, the band edge signal loss is 3 dB.

Using $g = \lambda/2.5$ in Eq. 5 gives

$$H_g \approx \left(\frac{2.3}{\lambda^{0.33}} + 1.63 \lambda^{0.22} \right) H_c \quad (7)$$

degaussing is very imp before test with density head/mc

For densities of 50 to 100 KFCI, λ is 1μ to 0.5μ and over that range the term in brackets above is nearly constant and equal to 4, hence

$$H_g \approx 4 H_c \quad (8)$$



If the record-reproduce head is ferrite, then $H_g \leq (4\pi M_s)/2$ and the result is that a coercivity of more than $H_c \approx (4\pi M_s)/8$ should not be used. The saturation flux density for MnZn ferrite is generally about 5000 G, so the maximum media coercivity one can safely use with a ferrite record-reproduce head is about $5000/8 \approx 625$ Oe.

NiZn ferrite should not be used because its $4\pi M_s$ is only 4100 G, which promotes saturation, and it tends to form a "dead layer" of several hundred angstroms which causes separation loss.

If the head is Sendust tipped, a gap field up to about $H_g \approx 0.8(4\pi M_s)$ can be used because the metal has a more rapid approach to saturation than does ferrite. Since $4\pi M_s \approx 9500$ G, Eq. (8) gives $H_c \leq 1900$ Oe, which is higher than that of any high density medium yet reported.

Saturation and Eddy Currents in Metal Heads

Although small gap Sendust tipped heads can record on very high coercivity media, at high frequencies, the flux is confined to the surface of the head by eddy currents in the conductive metal. This causes the gap field to be shifted in phase relative to the record current by various amounts, depending on frequency. In addition, because of saturation in the "skin" of the head, the efficiency E in Eq. 1, and hence H_g , can become much smaller, for constant record current, as the record frequency is increased. For example, experiments at various tape speeds indicate that the efficiency of the 0.25μ gap length Sendust tipped heads used in generating Figure 4 decreases from 52% at 10 KHz to only about 9% at 10 MHz. If a constant record current is used in these or other metal heads while recording high frequency digital data, long strings of zeros (low frequencies) will be severely over-recorded, which causes peak shift and resultant errors. Even if record pre-emphasis is used to prevent this over-recording effect, there will still be lots of hard to predict phase shift occurring in the record head itself because of the eddy current induced saturation. This phase shift will change as the head wears. The frequency/saturation effect makes the Sendust tipped head shown in Figure 5 a poor choice for high frequency use.

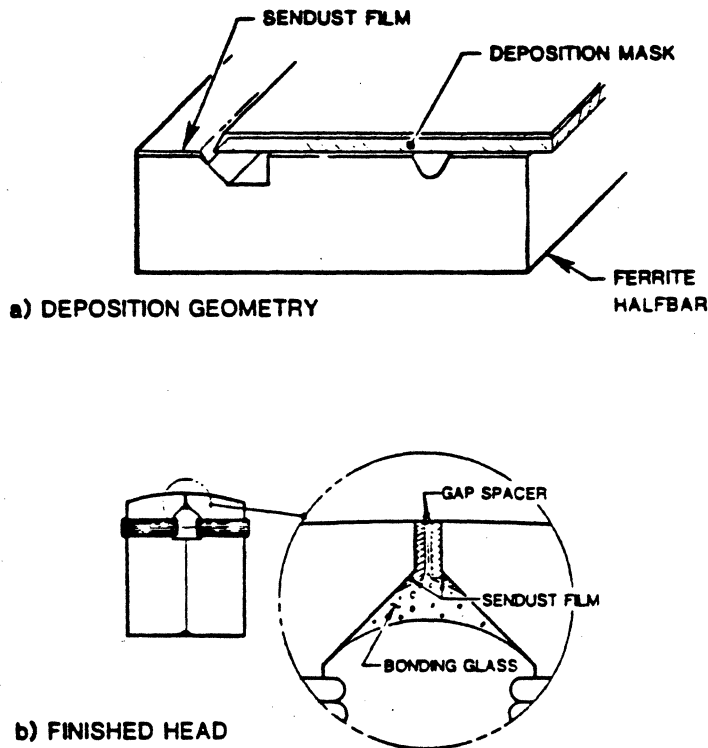
Heads have been made of crystalline Sendust and amorphous metallic quench-cooled ribbons.^{8,9} These heads are easy to make in thin laminations, so they suffer less high frequency degradation from eddy currents than unlaminated heads. The resistivity of the amorphous ribbons is higher than Sendust so eddy currents are even less important, but the wear rate for several amorphous materials tested at Spin Physics was about 5 times higher than Sendust. The high wear rates of amorphous metals has recently been confirmed.¹⁰

Metal-In-Gap Head

Figure 9 shows a new type of Sendust-ferrite composite head, where the Sendust is sputter deposited on the gap faces of an otherwise all ferrite head, thus the name Metal-In-Gap or MIG.⁴

8. N. Tsuya, et al. IEEE Trans. on Mag., Vol. Mag. 17, No. 6, Nov. 1982, pg. 3111.
9. K. Shiki, et al. J. Appl. Phys., Vol. 52, No. 3, March 1981, pg. 2483.
10. R. Ozawa, IEEE Trans. on Mag. Vol. Mag 20, pg 425, March 1984.

FIG. 9 CONSTRUCTION OF MIG HEAD

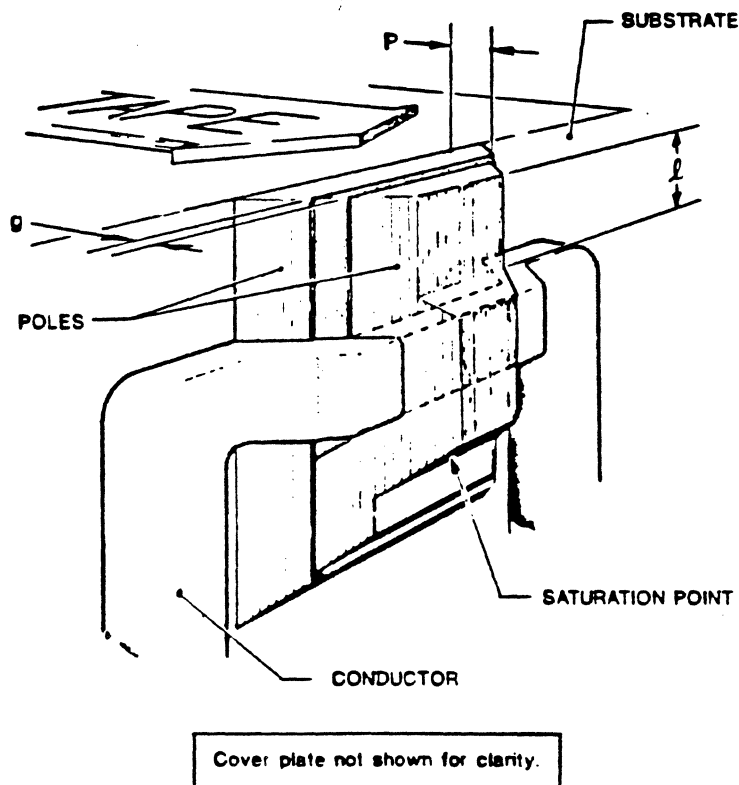


Since the Sendust film and the ferrite core are magnetically in series, H_g is limited to the $4\pi M_s$ of the ferrite which is about 5000G. Because the Sendust $4\pi M_s = 9500$ G, the gap edges do not saturate at this gap field and the maximum gap field for the MIG is $H_g = 5000$ Oe. Using Eq. 3, we see that an $H_c = 1250$ Oe can be used with an MIG record/reproduce head without pole tip saturation being a problem. The efficiency of this head is much less frequency dependant than that of the metal tipped head, and so it is fine for recording digital data at high frequencies on high coercivity media. The reason that the MIG curve in Figure 8 is not as high as that of the Sendust tipped head is probably because of a small amount of "pole tip washout" induced record separation loss. See Figure 14. This effect is much less important at high media speeds.

Thin-Film Record Heads

A simple one turn thin-film head is shown in Figure 10. Multiple turn heads have also been made.¹¹ The poles are typically sputter deposited or electroplated 81% nickel and 19% iron, having a permeability of about 2500 and a $4\pi M_s$ of 10^4 G. The structure is fabricated photolithographically. Integrated circuits are made in a similar way.

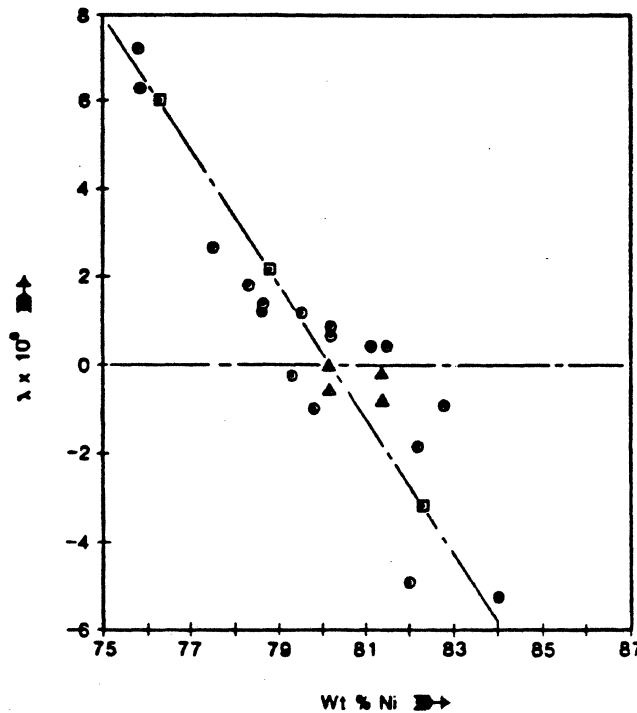
FIG.10 SINGLE TURN THIN FILM HEAD



The composition of 81/19 NiFe is important, because its magnetostriction constant is zero. Figure 11 shows the magnetostriction constant plotted versus composition. When films are deposited at an oblique angle, as occurs at the "shoulders" in Figure 11, the films are invariably strained to some degree. If λ is not very small, this strain can reduce the effective permeability of the shoulders by a factor of 5 or 10 and hence, drastically reduce the head efficiency.

11. N. Wakabayashi, IEEE, Trans. on Mag., Vol. Mag. 18, No. 6, Nov. 1982, pg. 1140.

FIG. 11 MAGNETOSTRICTION VERSUS COMPOSITION FOR Ni/Fe



Journal Of Applied Physics, Vol. 52, No. 3, March 1981, p 2475

The pole thickness p , for high density recording, is typically about 4μ . This thickness is about the maximum that can be processed conveniently, by photoresist and ion mill etching, at the $\approx 3\mu$ line width resolution required for high track density multi-track heads. Track densities of up to about 500 TPI on two interleaved stacks can be made this way. The gap depth l is determined by the wear rate of the substrate and the expected life of the head. The gap depth needs to be as small as possible because the ratio p/l determines the maximum H_g that can be generated.

At low gap fields, (and in reproduce) the efficiency of this sort of head is generally high when $p \approx l$.^{12,13} However, when the gap flux (per unit track width) $H_g l$ approaches the pole layer saturation flux $4\pi M_s p$, the core saturates in the region noted in Figure 10 and no further gap field increase occurs. The saturation gap field is given by Eq. 9.

12. R. Jones, IEEE Trans. on Mag., Vol. Mag 14, 1978, pg. 509.

13. K. Kanai, IEEE Trans. on Mag., Vol. Mag. 15, 1979, pg. 1130.

$$H_g^{\max} \approx 4 \pi M_s \frac{p}{l} \quad (9)$$

Figure 12 shows a sketch of the gap field versus record current i_r for $g = 0.25\mu$ and various p/l values.

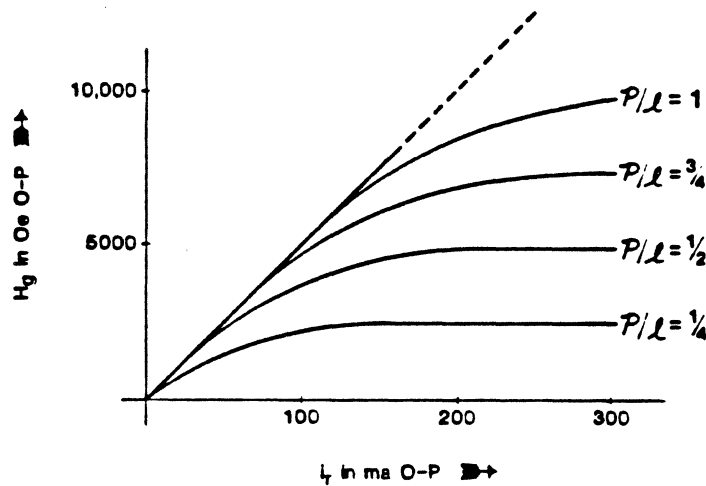


FIG.12 H_g versus i_r for single turn record head with $g = 0.25 \mu$ and various p/l values.

Figure 13 shows a sketch of the 80 KFCI signal recorded by a 0.25μ gap single turn record head, having two gap depths, plotted versus record current in dB. Also plotted is the corresponding curve for a Sendust tipped head, which does not saturate in this current range. The curves in Figure 8 have been shifted horizontally to compensate for differences in low field efficiency.

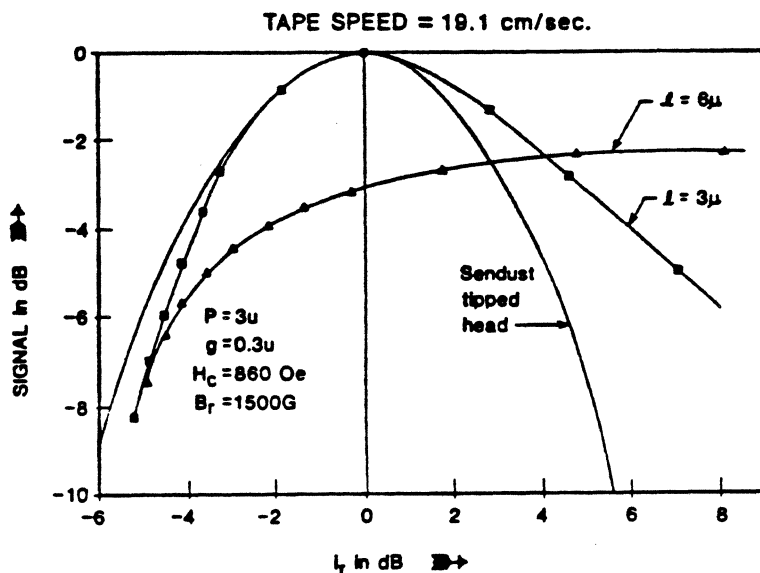


FIG.13 80 KFCI or $\lambda = 0.635 \mu$ signal level versus record current for a single turn head.

As may be seen, the $p = 3\mu$, $l = 3\mu$ head does succeed in "saturating" the tape while the $l = 6\mu$ head does not. Zero dB is 180 ma pp for the $l = 3\mu$ curve.

If a MnZn ferrite substrate is used, the bottom pole can be eliminated. If the top deposited pole is downstream of the gap, the partial saturation of the ferrite gap corner is of little concern because it is so far from the record zone.

Head Wear

Because of the stringent requirement for minimum head to medium spacing, the head to medium pressures may need to be high, which increases the wear rate. As the gap is reduced, so is gap depth, in order to maintain head efficiency. Hence, head life is reduced.

Fortunately, thin-film and MIG head materials such as sapphire and ferrite are much more resistant to wear than Sendust and permalloy used in conventional heads. The wear rate of ferrite is about 10 times less than that of Sendust, and the wear rate of sapphire is so small that it is difficult to measure.

An important problem with MIG and thin-film heads running in contact, is that the softer metal layers tend to erode due to differential wear, as sketched in Figure 14. Since so little metal is exposed, the undercut is only about 0.05μ , but at a recording density of 100 KFCI, even this tiny amount gives about 4.5 dB record and 5.5 dB of reproduce separation loss for a total of 10 dB. This effect is much less important at high medium speed.

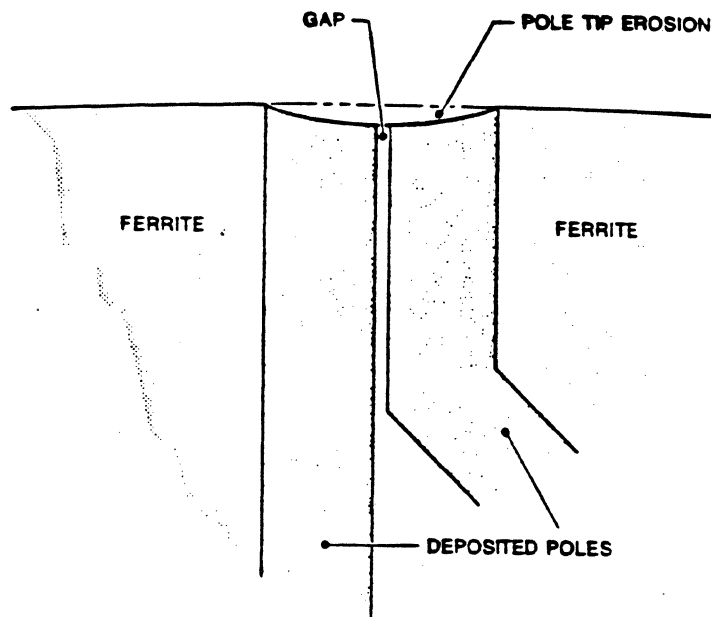


FIG. 14 MIG and thin film head showing pole tip erosion.

Record Heads for Thin-Film Media

Eq. 5 relating H_g, λ, g and H_c was obtained from data generated using thick particulate coated media. If deposited thin-film media are being recorded, where the media thickness is comparable to the record gap, Eq. 5 does not hold and ferrite heads can be used with H_c values much higher than 625 Oe. Here one assumes that $H = H_c$ at the back of the medium as sketched in Figure 15.

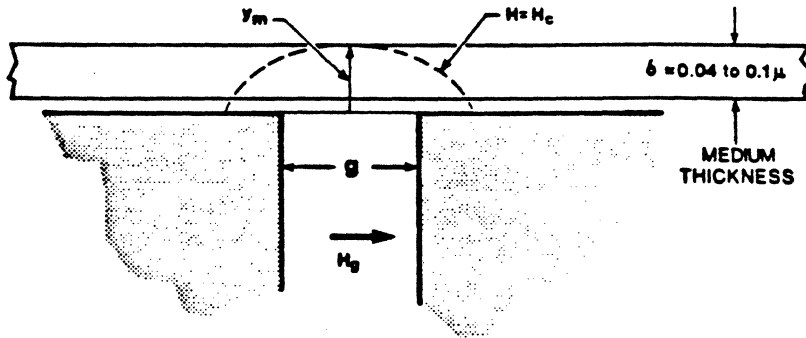


FIG. 15 RECORD CONTOUR FOR THIN FILM MEDIA.

The field is written in terms of the Karlqvist approximation.¹⁴

$$H_x = \frac{H_g}{\pi} (A1 - A2) \quad (10)$$

and

$$H_y = \frac{H_g}{\pi} \ln (R1/R2) \quad (11)$$

where the angles and distances are defined in Figure 16.

14. O. Karlqvist, Trans. R. Inst. Tech. Sweden, Vol. 86, Oct. 1954, pg. 2.

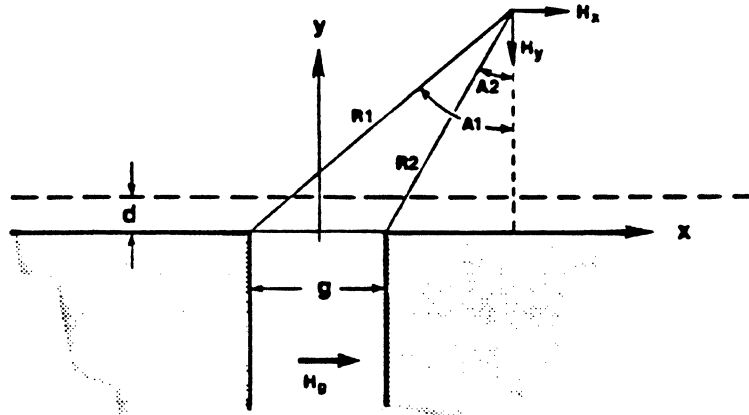


FIG. 16 ANGLE & DISTANCE FOR EQUATIONS 10 & 11.

These expressions were used to sketch the field contours in Figure 2 where $H = |\vec{H}| = \sqrt{(H_x)^2 + (H_y)^2}$. Defining Y_m to be the height of the $H = H_c$ contour at the back of the medium, we have

$$\begin{aligned} \frac{Y_m}{g} &= \left[2 \tan \left(\frac{\pi H_c}{2 H_g} \right) \right]^{-1} \\ &\approx \frac{1}{2.95} \left(\frac{H_g}{H_c} \right) - 0.15 \end{aligned} \tag{12}$$

The exact expression and approximation are plotted in Figure 17. The approximation is good for $y/g \geq 0.4$ and is easier to calculate.

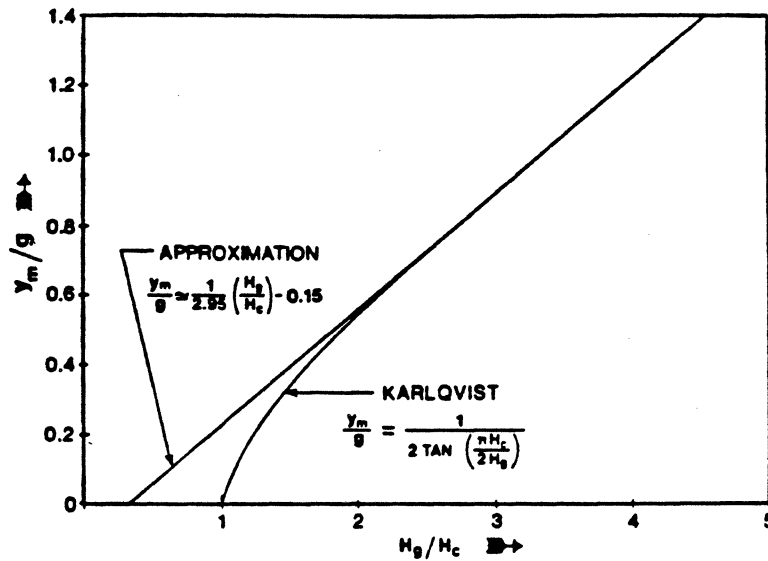


FIG. 17 PLOT OF $\frac{Y_m}{g}$ VERSUS $\frac{H_g}{H_c}$

Solving Eq. 12 for H_c and saying $H_g \leq (4\pi M_s)/2 = 2500$ Oe for the ferrite head material, gives

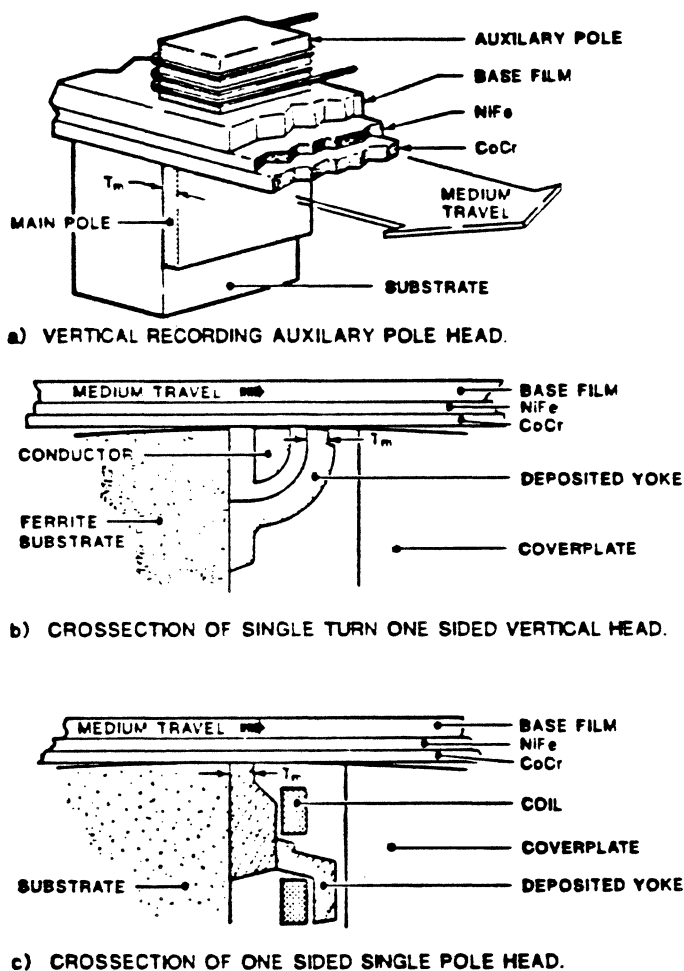
$$H_c \lesssim 847 / \left(\frac{Y_m}{g} + 0.15 \right) \quad (13)$$

If $Y_m/g = 0.5$, Eq. 13 gives $H_c \leq 1300$ Oe for the maximum H_c that can be used with a ferrite head when the medium is very thin. This is a factor of two higher than the 625 Oe upper bound determined previously for thick media.

Vertical Recording Heads

In vertically oriented media such as sputter deposited CoCr,¹⁵ the demag fields coming from the previously recorded bit, aid the record field in recording the next bit, rather than opposing it as in conventional media. This results in a narrower record zone, hence, a larger high density signal and less non-linear bit shift. Conventional ring record heads work well with vertical media because, at the surface of the media where most of the high density signal resides, the record field is vertical. However, a narrower record zone and improved record performance is obtained with "vertical pole heads" as sketched in Figure 18 when recording on two layer vertical media.¹⁵

FIG. 18 VERTICAL HEADS



anisotropy in FeNi underlayer causes modulation in once around signal.

working structure.

15. Iwasaki, IEEE Trans. on Mag., Vol. Mag 18, No. 6, Nov. 1982, pg. 1110.

Toda¹⁶ has compared the record capability of the head shown in Figure 18c, having a pole thickness T_m of 1.2μ , to a ferrite ring head giving a gap of 0.16μ . Both were tested on a two layer CoCr medium. The pole head recorded up to 7.6 dB more signal than the ring head and the ring head pulses were very asymmetric. This indicates that significant horizontal moment, as well as vertical, was recorded by the ring head, which complicates reproduction. Pole heads seem better than ring heads for recording on two layer vertical media.

However, when recording on single layer vertical media, very high current levels are required with pole heads because demagnetization fields in the pole tip are very high. Magnetomotive forces, Ni_r , of 30 amp turns are common for the single layer, while 2 amp turns are needed for the two layer medium, because of the "magnetic image" of the record head provided by the NiFe layer.

Okuwaki¹⁷ has shown that D50 densities (where the signal is down 50%) of 70 KFCI can be recorded successfully on single layer CoCr media, with very little pulse asymmetry using ring heads, if the CoCr anisotropy field is large.

Reproduce

The output voltage of an inductive reproduce head is given by

$$S = -10^{-8} N \frac{d\phi}{dt} \quad (14)$$

where S is in volts, N is the number of turns, and ϕ is the flux in the head in Maxwells (cgs emu or Gauss cm^2). The head flux ϕ is determined by the reciprocity principle¹⁸

$$\phi = \int \bar{M}_r \cdot \bar{H} dV \quad (15)$$

16. J. Toda, IEEE Trans. on Mag., Vol. Mag 18, No. 6, pg. 1164, Nov. 1982.

17. T. Okuwaki, J. Appl. Phys., Vol. 53, No. 3, pg. 2588, March 1982.

18. W. Westmijze, Philips Res. Rep., 8, 1953, pg. 148.

Spacing loss
in vertical rec
≡ long. rec $99 \frac{\lambda}{T}$

where M_r is the recorded remanence in the medium and $\bar{H}$ is the field above the read head generated by a unit "test current" in the reproduce windings. The integral is over the volume of the tape. For a ring head, $\bar{H}$ is given by equations 10 and 11 and in this context is called the "Read Head Sensitivity Function." Equation 15 can be broken down into horizontal and vertical components as

$$\Phi = \int M_{rx} H_x d\nu + \int M_{ry} H_y d\nu \quad (15a)$$

If $M_{rx} = M_{ry}$ are the amplitudes of respective sine waves, the two terms above are equal except for a 90° phase shift, hence equal horizontal and vertical sine wave magnetizations produce the same read signal amplitude.

We can get a rough idea of the expected signal amplitude S if we make the crude approximation that the medium is sinusoidally magnetized at the saturation level, i.e.

$$M_{rx} = M_{rs} \sin\left(\frac{2\pi}{\lambda} x\right) \quad (16)$$

to a depth Y_m and is unmagnetized beyond that. Eq. 15a can then be easily integrated to give the simple expression

$$S = A e^{-(2\pi+5)d/\lambda} [1 - e^{-2\pi \delta/\lambda}] \quad (17)$$

$$\cdot \frac{\sin(1.14 \pi g/\lambda)}{(1.14 \pi g/\lambda)} \quad \text{p-p in Volts}$$

where

$$A = 2 \times 10^{-8} \text{ ENT} \sqrt{4\pi M_{rs}} \quad (18)$$

The first term in the exponent in Eq. 17, $-2\pi d/\lambda$, gives the $-55d/\lambda$ dB reproduce separation loss, and the second, $-5d/\lambda$, gives the $-44d/\lambda$ dB record separation loss, both discussed earlier. The record separation term did not come from Eq. 15a but was added ad hoc. The term in brackets is the "thickness loss term" and gives "6dB/octave" increase at long wavelength and shows that 90% of the signal comes from the top λ/e of the layer. Hence, little is gained by making $\delta > \lambda/e$. The third term is the "gap loss term." It is unity at long wavelength and zero when $\lambda = 1.14g$,¹⁸ having subsequent "bumps" as the wavelength is further reduced.

E in Eq. 18 is the reproduce head efficiency given by Eq. 2, or more accurately, by equations in Ref. 1. N is the number of turns on the reproduce head, T is the track width in cm and v is the media velocity in cm/sec. $4\pi M_{rs}$ is the saturation remanence flux density in Gauss, i.e. 100% in Figure 1 or about 1200 Gauss for most tapes.

Figure 19 shows a response curve obtained using the 0.25μ gap record head, a 0.25μ gap reproduce head and tape used to obtain the data shown in Figure 4.

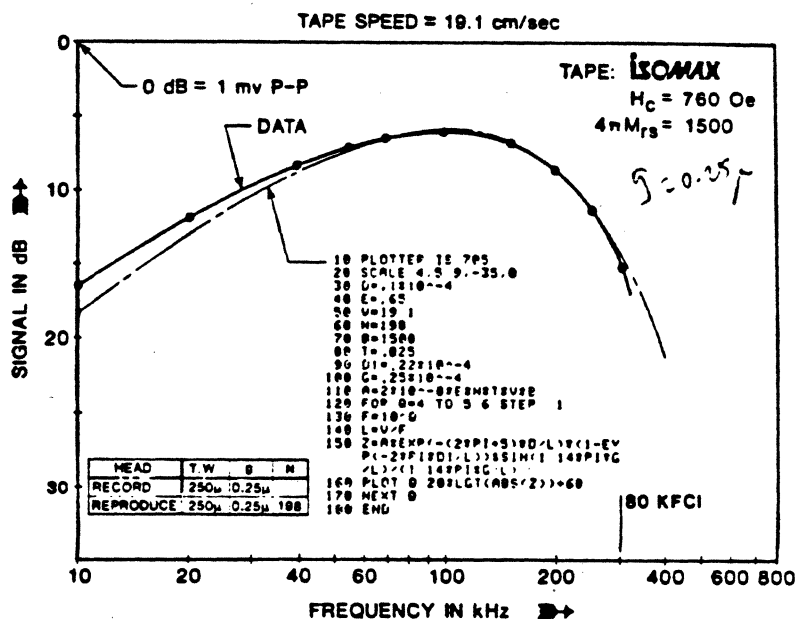


FIG. 19 SINEWAVE RESPONSE CURVE AND COMPUTER FIT.

The recording was unbiased sinewave, with the record current held constant and set to maximize the 300 KHz or $\lambda = 0.635\mu$ signal. Using a record gap $g = 0.25\mu$ and $\lambda = 0.635\mu$ in Eq. 5 gives $H_g/H_c \approx 4.2$. Using this in Eq. 12 gives $Y_m/g \approx 1.27$ or $Y_m \approx 0.32\mu$. $4\pi M_{rs}$ for the tape used was 1500 G, the reproduce turns were $N = 198$, the track width was $T = 0.025$ cm, and the tape speed was $v = 19.1$ cm/sec. The reproduce gap was also 0.25μ . A reasonable upper bound on the reproduce head efficiency was $E \approx 0.65$ and a head tape separation of $d = 0.1\mu$ was picked to give a good fit. Using these values in Eq. 17 and Eq. 18, gives the HP-85 computer drawn curve in Figure 19. The program is also shown. The fit is within about 2 dB which is surprising considering the gross approximations made.

In digital recording one records "square waves." Figure 20 shows the data in Figure 19 and a square wave response curve done at the same time. At short wavelengths the higher odd harmonics which make up the square wave do not come through the record/reproduce process so the sine and square wave signals are the same.

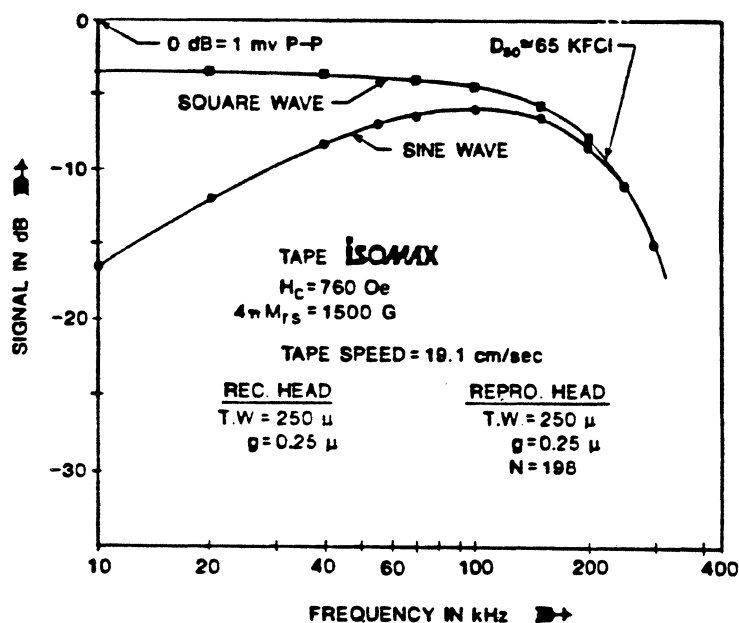
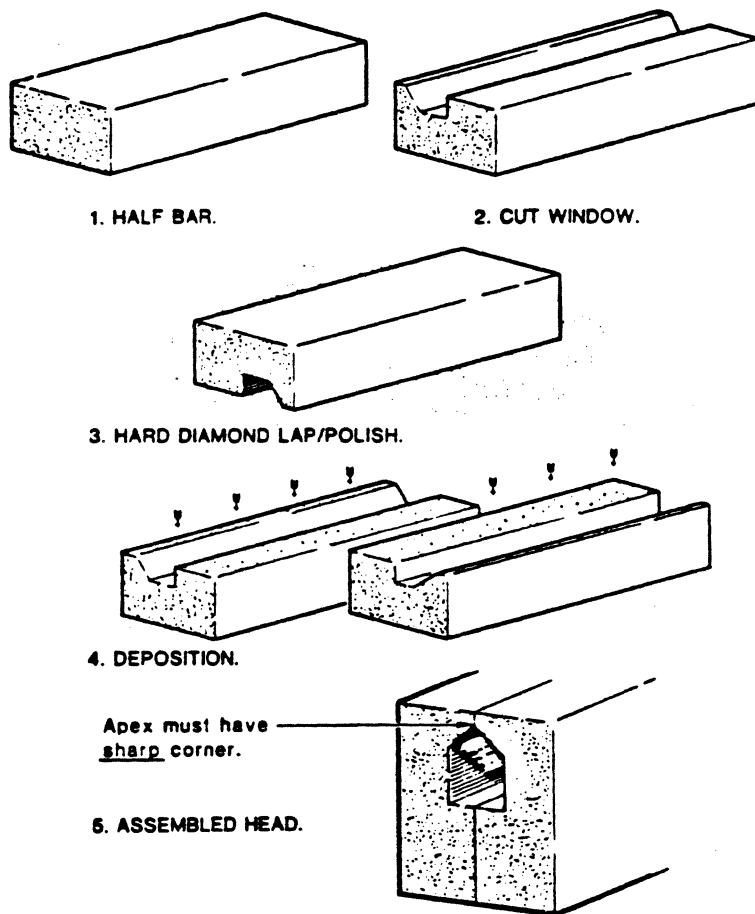


FIG. 20 COMPARISON OF SINEWAVE AND SQUAREWAVE RECORDING. RECORD AND REPRODUCE HEADS ARE SENDUST TIPPED.

Gap Edge Straightness

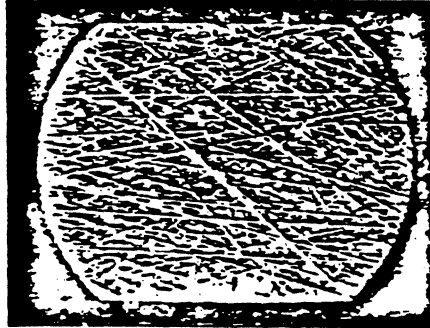
In the past, the standard procedure for making heads has been to cut the "current window" and then polish the gap surfaces. Because of this sequence, the final polish must be a hard diamond lap in order to preserve a sharp corner at the gap apex, as sketched in Figure 21.

FIG. 21 TRADITIONAL HEAD CONSTRUCTION.

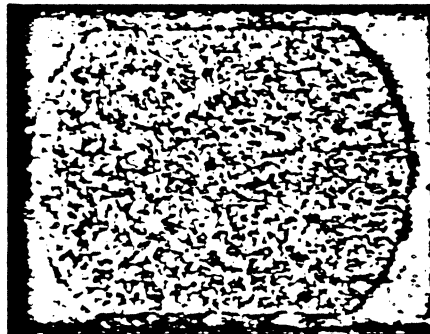


This procedure results in a gap surface covered with tiny scratches. Figure 22 shows typical gap surfaces of ferrite and Sendust tipped heads.

FIG. 22 DIAMOND LAPPED GAP SURFACES AT 950X



FERRITE HEAD GAP SURFACE.



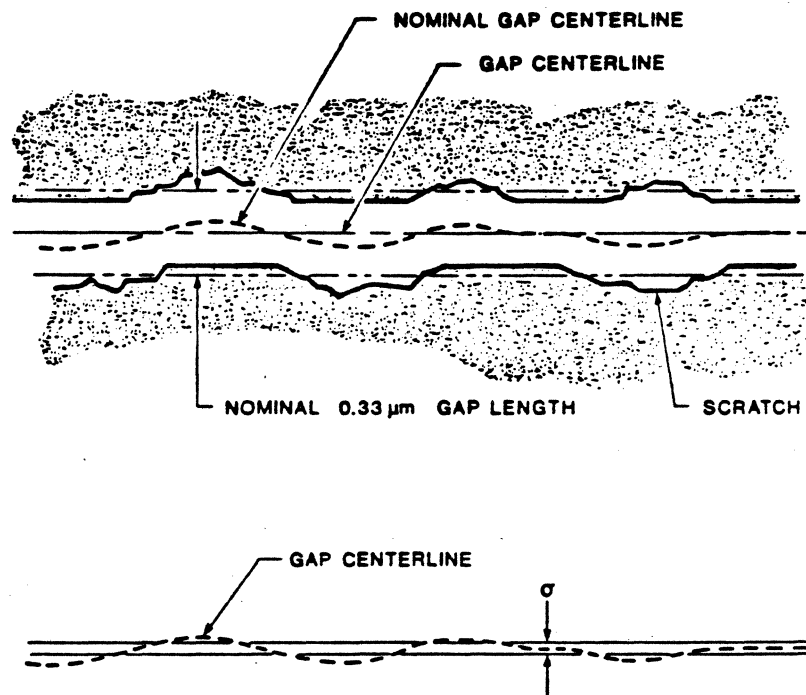
SENDUST TIP GAP SURFACE.

*Sendust is
inhomogeneous
material
causes bright lines
during polishing.*

The contrast of these photos has been greatly increased with Nomarski differential interference enhancement.

The smallest scratches are too small to measure, but the larger ones are as large as 1μ across and probably up to 0.5μ deep. When the head is assembled, the gap looks, in a somewhat exaggerated way, as shown in Figure 23.

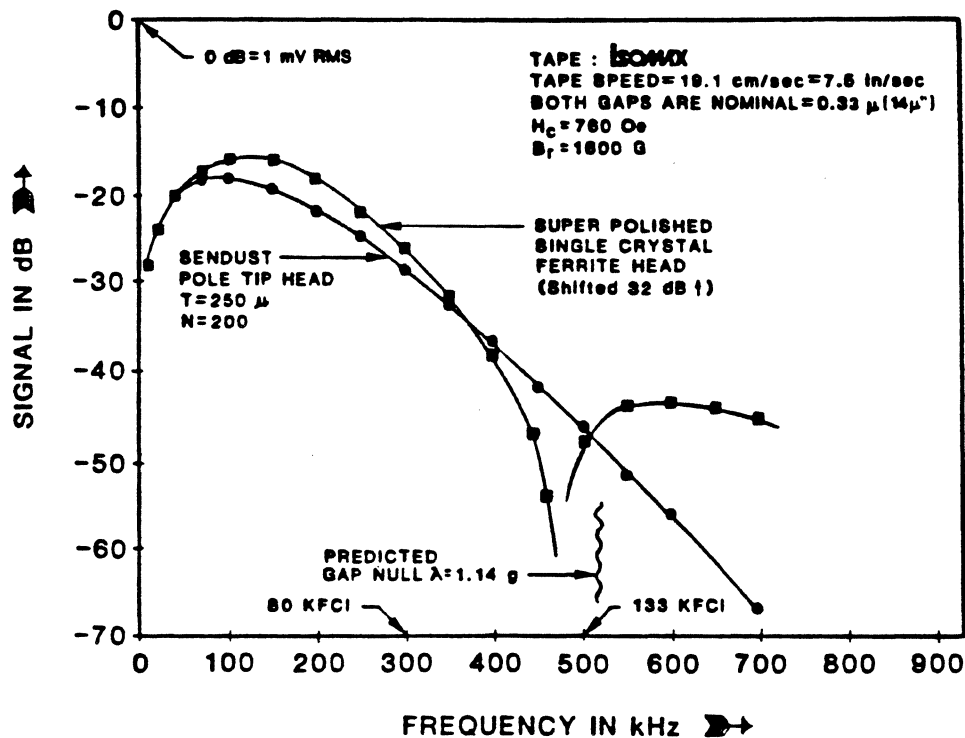
FIG. 23 Top view of a head with scratched gap faces at about 50,000X (I).



σ = RMS GAP CENTERLINE STRAIGHTNESS DEVIATION

The gap length variation shown in Figure 23 washes out the gap null. Figure 24 shows a 250μ track width Sendust pole tip reproduce head spectrum, which is linear through where the gap null should be. Also shown in Figure 24, is the reproduce spectrum of a 36μ track width single crystal MnZn video head with the same gap.

FIG. 24 RESPONSE CURVE SHOWING REPRODUCE GAP NULL BEHAVIOR.



The ferrite head curve was shifted up to compensate for differences in track width, turns and core efficiency. The ferrite head shows the expected gap null because its gap surface was "superpolished" using a colloidal SiO_2 lap¹⁹ which results in a surface finish as is shown in Figure 25. Nearly all of the artifacts visible are dust in the microscope optical path.

19. T. Wada, IEEE, Trans. on Mag., Vol. Mag. 16, No. 5, 1980, pg. 884.

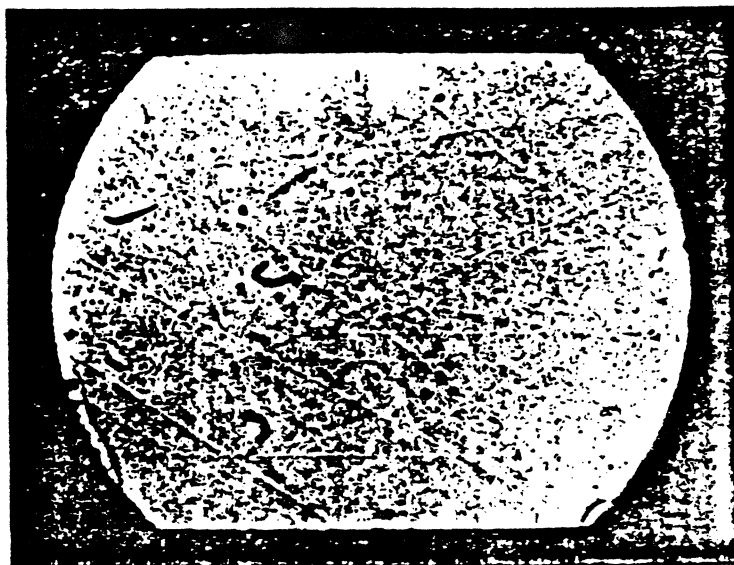


FIG. 25 FUJI Mn Zn SINGLE CRYSTAL
SUPER POLISHED WITH
COLLOIDAL SiO₂ AT 950X.

This lapping technique results in a close to perfect surface finish but it tends to round off corners so it is necessary to lapp the gap surface and then cut the current window to preserve the sharp corner at the gap apex. This requires care to avoid chipping.

The important thing to note in Figure 24, is that the reproduced signal at intermediate and bandedge densities is up to 3 dB higher for the ferrite head. The reason for this, is that the gap center line for the Sendust tipped head is not straight, as shown in Figure 23. When this occurs, various parts of the recorded track produce signals that are out of phase and tend to cancel, resulting in less signal. Mallinson²⁰ has shown that if σ represents the average gap centerline deviation, then the "gap irregularity loss" on reproduce is given by

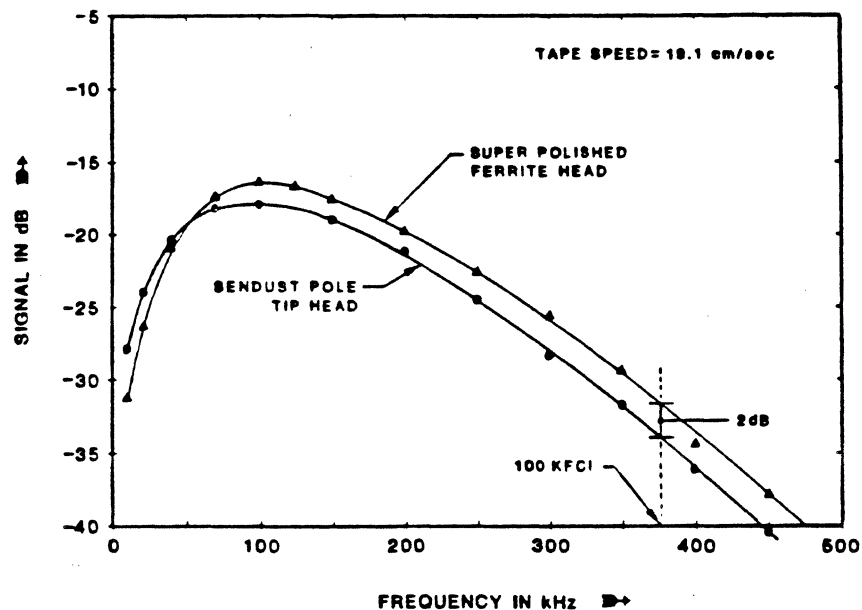
$$\text{Gap Irreg. Loss} \approx 169 \left(\frac{\sigma}{\lambda} \right)^2 bB \quad (19)$$

20. J. Mallinson, IEEE, Trans. on Mag., March 1969, pg. 71.

Noting that the difference between the ferrite and Sendust tipped heads is 3 dB at 200 KHz or $\lambda = 0.95\mu$, solving (19) for σ gives $\sigma = 0.18\mu$ which is reasonable in view of the picture shown in Figure 22.

Figure 26 shows the comparative record spectra of the two heads. The "superpolished" ferrite head curve was adjusted upward to compensate for track width differences. Both curves were reproduced with the same Sendust pole tip read head, hence, no gap null is evident.

FIG. 26 RECORD PERFORMANCE OF SENDUST TIPPED AND SUPER POLISHED FERRITE HEADS.



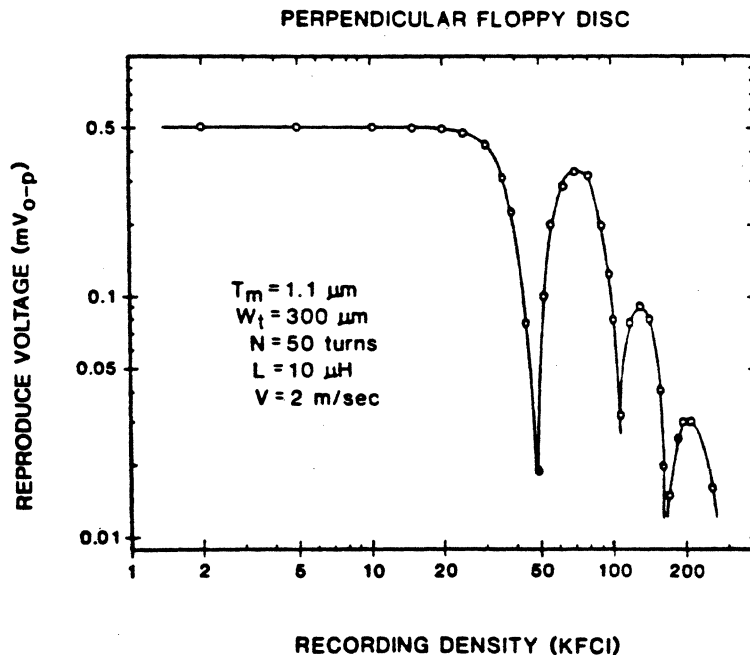
The "superpolished" ferrite head records about 2 dB more mid-range and high-density signal and the advantage is independent of wavelength for $\lambda \leq 1.75\mu$. The source of this advantage is not obvious. The local "record phase cancellation" one might expect from the gap centerline deviation of the Sendust tipped head is apparently compensated by gap length variations. Where the gap is small, the record fields are large and vice versa. This might tend to straighten out the recorded transitions.

One possible explanation for the more or less wavelength independent advantage of the "superpolished" head is that there will be significant record field direction variation along the Sendust tipped head gap. Since Isomax medium accepts magnetization in any direction, the net result could be a reduced component in the tape travel direction at the surface of the tape, and hence a reduced signal at medium to short wavelengths. The straight gap edges of the ferrite head record full magnetization in the tape travel direction which gives maximum detected signal. Note that this ferrite head records very well on this $H_c = 800 \text{ Oe}$ tape in spite of a small amount of gap edge saturation.

Vertical Pole Heads in Reproduce

The vertical heads shown in Figure 18 work well in recording on vertical media, but in reproduce they suffer from "gap nulls" caused by the thickness of the main pole T_m . Figure 27 shows a typical example where $T_m = 1.1 \mu$.

FIG. 27 VERTICAL POLE HEAD
RECORD/REPRODUCE



This head is not useable beyond about 40 KFCI. If T_m is reduced, to move the gap nulls out to higher density, the record function suffers, apparently because of pole tip saturation, and the medium thickness must be reduced, which lowers mid-band and low density signal.¹⁶

Magnetoresistive Read Heads

Magnetoresistive or MR heads generally use a 200-500 Å thick "single domain" layer of 81/19 NiFe permalloy, whose resistivity changes, in response to rotation of the film magnetization vector, according to the expression.²¹

$$\rho = \rho_0 + \Delta\rho \cos^2 \theta \quad (20)$$

Where θ is the angle between the current and the magnetization of the film, ρ_0 is the isotropic resistivity, and $\Delta\rho$ is the magnetoresistivity. The deposition takes place in a magnetic field which gives rise to an internal "anisotropy field" H_k . This field exerts a torque on the magnetization which acts to keep $\theta = 0^\circ$, the so called "easy axis." H_k is about 3 to 10 Oe. The sensor carries a constant sense current i_s and the field from the recorded medium rotates the moment, changing the resistance, which varies the voltage across the MR element, hence producing a signal. Figure 28 shows a sketch of an MR element.

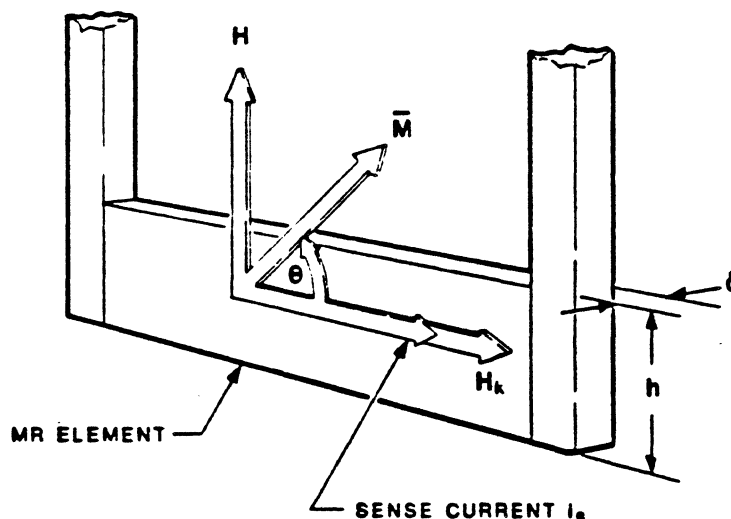


FIG. 28 MR ELEMENT

21. D. Thompson, IEEE, Trans. on Mag., Vol. Mag. 11, No. 4, 1975, pg. 1039.

Figure 29 is a sketch of $(\rho - \rho_0)/\rho_0$ versus applied field H . The "skirts" of the curve are due to minor local deviations in the direction and magnitude of the anisotropy field H_k , called "dispersion," and also due to any (non uniform) demagnetizing fields H_d that may exist. The dotted curve in Figure 29 shows how a "perfect" film would behave.

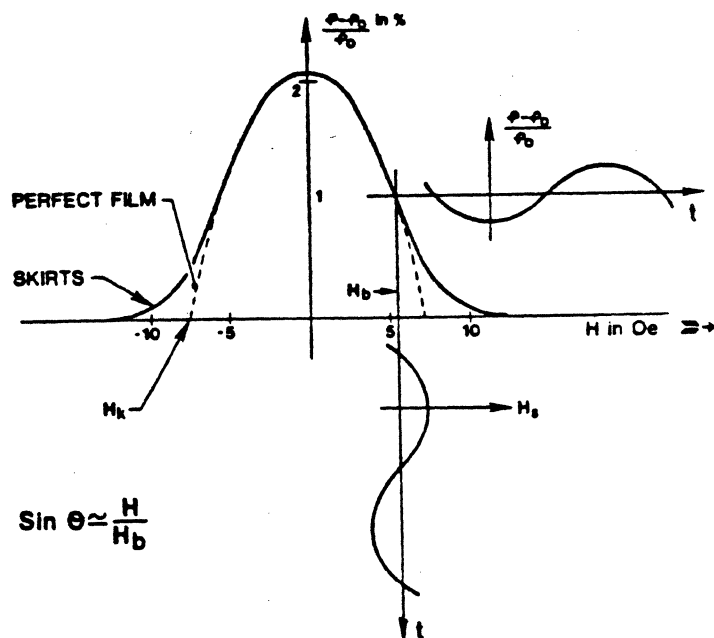


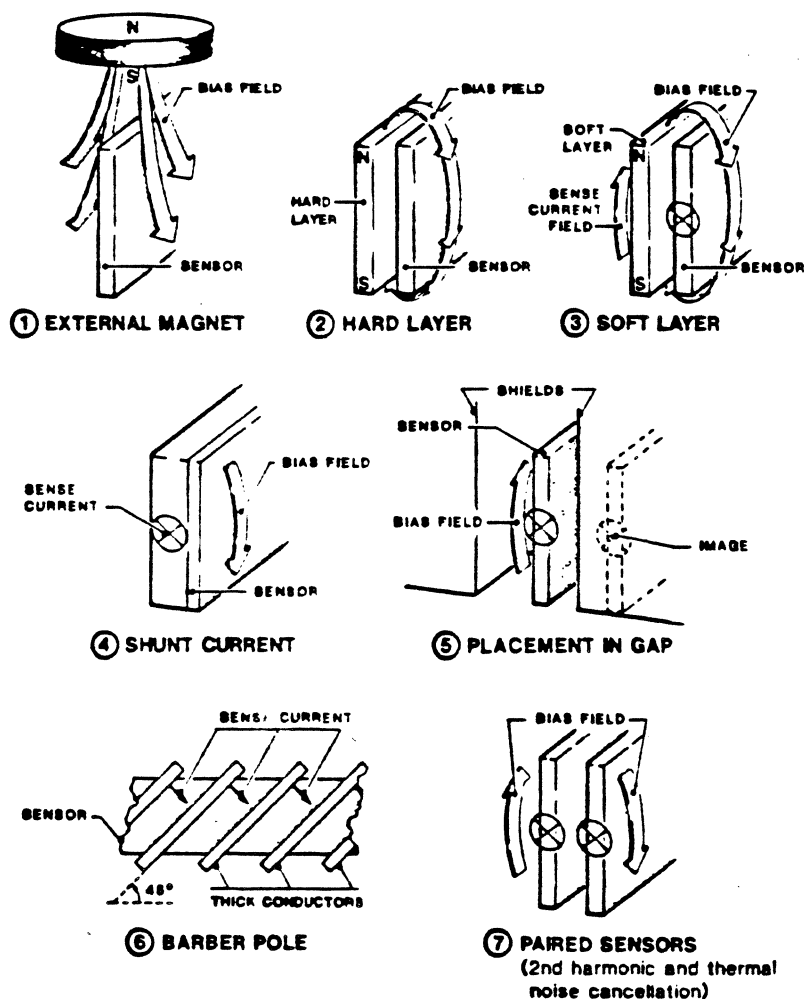
FIG. 29 SKETCH OF $\frac{\rho - \rho_0}{\rho_0}$ VERSUS H .

The element is subjected to a constant bias field H_b to move the operating point field to the inflection point in the curve so as to get maximum signal and minimum 2nd harmonic distortion. This generally corresponds to $\theta \approx 45^\circ$. Standard signal in/out versus time sketches are shown in Figure 29.

The resistivity ρ_0 of permalloy is about $20\text{--}25\mu\Omega\text{cm}$, depending on thickness. $\Delta\rho$ is about $0.55\mu\Omega\text{cm}$ so $\Delta\rho/\rho_0$ 2.5%. When the element is deposited on a high thermal conductivity substrate, such as silicon or sapphire, current densities up to about $j \approx 10^7$ amps/cm² can be handled. This corresponds to an internal electric field of $E = j\rho \approx 200$ volts/cm. For an element length of 50 (2 mils) the applied voltage V is a nominal 1 volt. The sensor temperature increase is about 20°C . Since the peak-to-peak $\Delta\rho/\rho_0$ is 2.5%, the maximum signal $S \approx V \Delta\rho/\rho_0 \approx 25$ mV. The non-linearities shown in Figure 25 limit the usable signal to about half this, or $\sim 10\text{mV}$ for a 50μ element length.

MR heads are typically classified in terms of how the bias field H_b is applied. Perhaps a dozen different bias techniques have been reported. These include external fields, adjacent hard and soft magnetic layers, shunt current in adjacent non-magnetic layers, asymmetric placement of the sensor element in a magnetic gap, rotation of the current by "barber pole" conductor layers placed on the sensor layer, paired sensors each current biasing the other and "canted easy axis." See Ref. 22 and others contained there. Bias has also been accomplished by "exchange coupling" between the MR element and an adjacent antiferromagnetic layer.²³ See Figures 30 and 31.

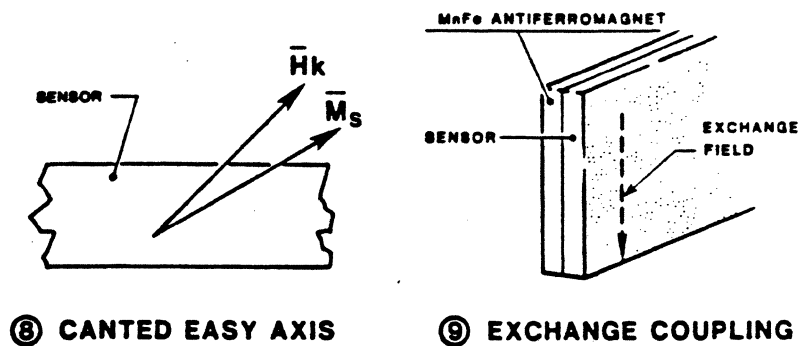
FIG. 30 MR HEADS BIAS TECHNIQUES



22. F. Jeffers, IEEE Trans. on Mag., Vol. Mag 15, No. 6, Nov. 1979, pg. 1628.

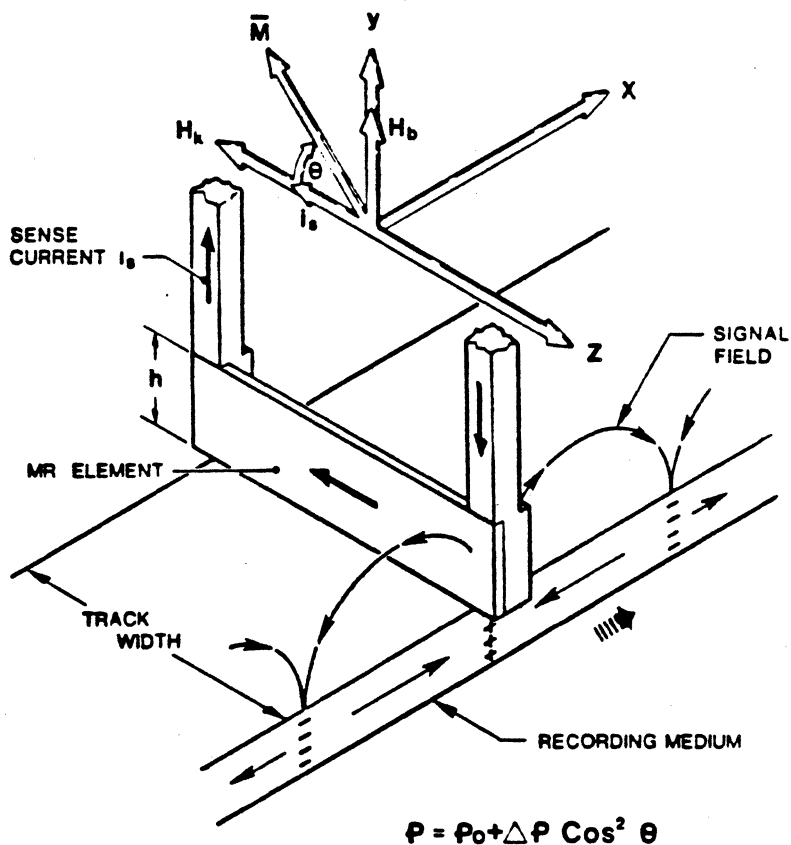
23. C. Tsang, Jour. Appl. Phys. Vol. 52, No. 3, March 1982, pg. 2471.

FIG. 31 (MR Heads Bias Techniques Cont.)



Discussion of all the above techniques is beyond the scope of this paper, but the simplest head due to Hunt²⁴ is instructive. Figure 32 is a sketch of the Hunt head. It responds to the vertical field above the media averaged over the element height h .

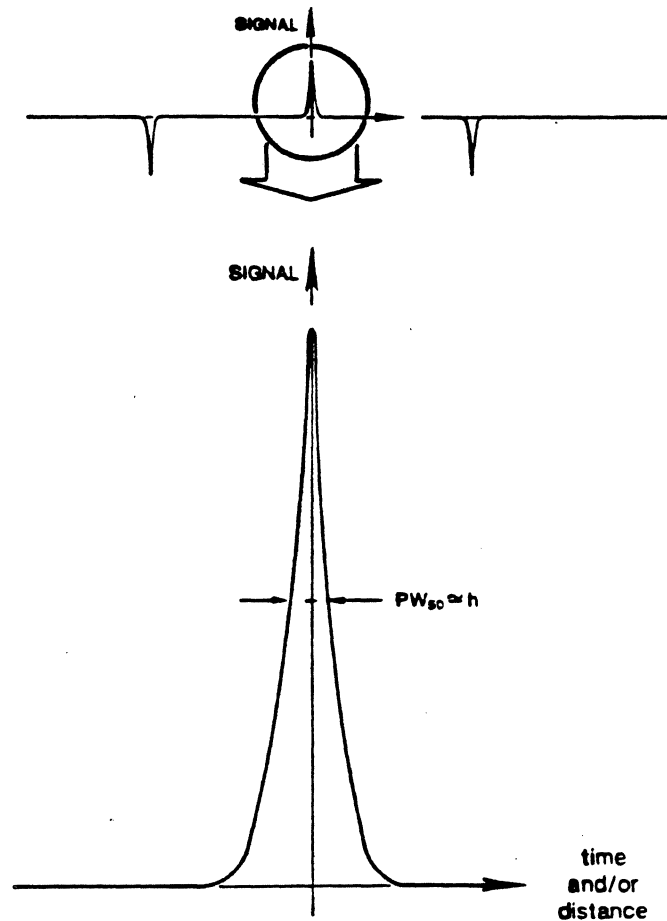
FIG. 32 UNSHIELDED MAGNETORESISTIVE HEAD



24. R. Hunt, IEEE Trans. on Mag., Vol. 7, pg. 150, No. 7, 1971, U.S. Patent #3,493,694.

The height must be more than $\sim 4\text{-}5\mu\text{m}$ or so, because of wear considerations. As a result, it detects approaching digital transitions before they are under the sensor. The isolated pulse shape is as shown in Figure 33.

FIG 33 HUNT HEAD ISOLATED PULSE SHAPE



The full width at half maximum $PW(50) \approx h$ for small head-medium separation. As a result, the signal spectrum covers a very large range as shown by Figure 34, where spectra for several elements are shown.²⁵

25. A.J. Collins and R.M. Jones, Int'l. Conf. on Video and Data Rec. July 1979.

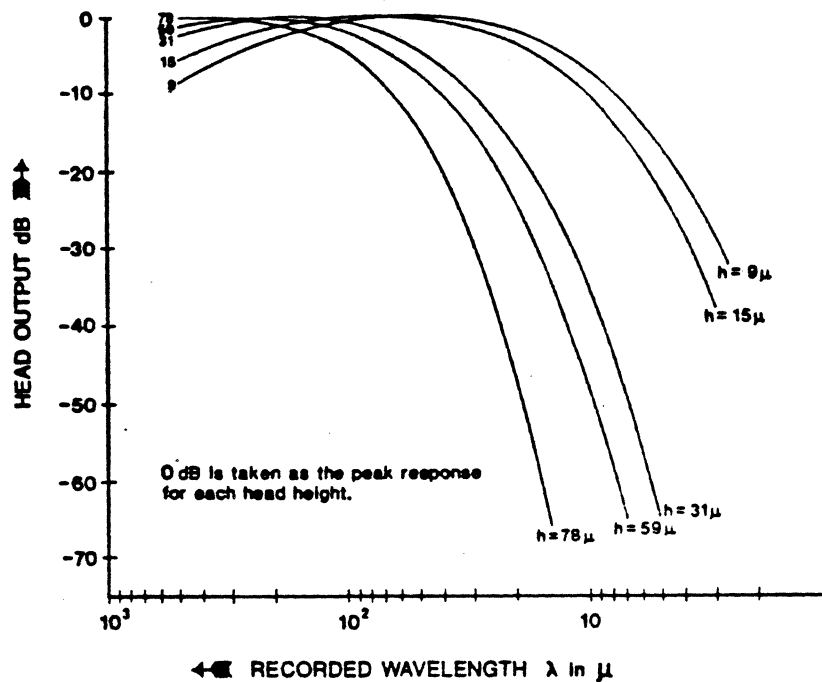


FIG. 34 FUNDAMENTAL FREQUENCY RESPONSES OF UNSHIELDED OPTIMALLY BIASED MR HEADS.

The "peak-to-band-edge" signal ratio, even for the $h = 9\mu\text{m}$ head, is about 40 dB for a $2\mu\text{m}$ band edge wavelength.

This signal is relatively free of amplitude or phase non-linearity and is equalizable. We presented a paper at the 1984 Intermag Conference describing the performance of a fully equalized unshielded MR head reproducing 80 KFCI data.²⁶

However, people have not wanted to equalize this much signal range so they put shields on either side of the MR element.²⁷ This has the result of reducing the long wavelength signal a lot and the short wavelength signal a lesser amount, so the peak to band edge ratio is smaller. Putting on the shields also creates a gap null at $\lambda \approx g$ where g is the sensor to shield spacing²⁸, but it is seldom observed because the sensor must be precisely centered in the gap.

26. F. Jeffers and H. Karsh, IEEE Trans. on Mag. Vol. Mag-20, No. 5, pg. 703, Sept. 1984.

27. A. Davies, IEEE Trans. on Mag., Vol. Mag. 11, No. 6, Nov. 1975, pg. 1689.

28. R. Potter, IEEE Trans. on Mag., Vol. Mag. 10, 1974, pg. 502.

The short wavelength loss of signal caused by the use of shields can be a serious problem if the electronic noise, which stays the same, causes the signal to noise ratio to decrease.

Another type of MR head is called a "yoke MR" and is sketched in Figure 35. Here the flux is collected by the yoke structure and conducted to the MR element, which is some distance removed from the media.

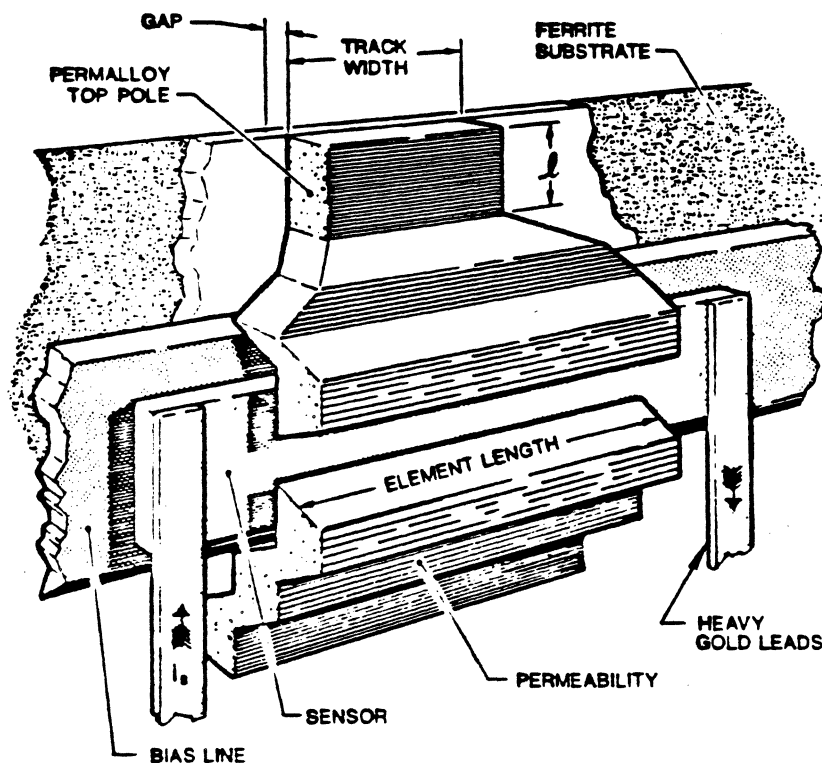


FIG. 35 YOKE MR HEAD
(Drawing not to scale)

Mr heads have more signal than inductive heads, at low media speeds. This is illustrated in Figure 36 where yoke MR signal is plotted versus $1/\lambda$. Also plotted is the output of a 200 turn inductive head, similar to that used in generating Figures 4 and 19, at various tape speeds. As the tape speed increases, the signal advantage enjoyed by the MR head decreases. However, care must be taken to avoid resonance effects in inductive reproduce heads. The 200 turn head discussed resonates at about 2 MHz, because of its relatively high inductance and unavoidable interwinding capacitance.

If an inductive head is properly designed for a given medium speed so that its self resonance frequency is about a factor of two above the upper band edge, increasing the medium speed by 2x requires a similar 2x reduction in the number of turns. Hence the inductive head signal is also independent of medium speed in that sense. A Hunt head as shown in Figure 32 will have a much larger signal than any inductive head at any medium speed, and it is much easier to design to achieve tape noise limited signal to noise performance.

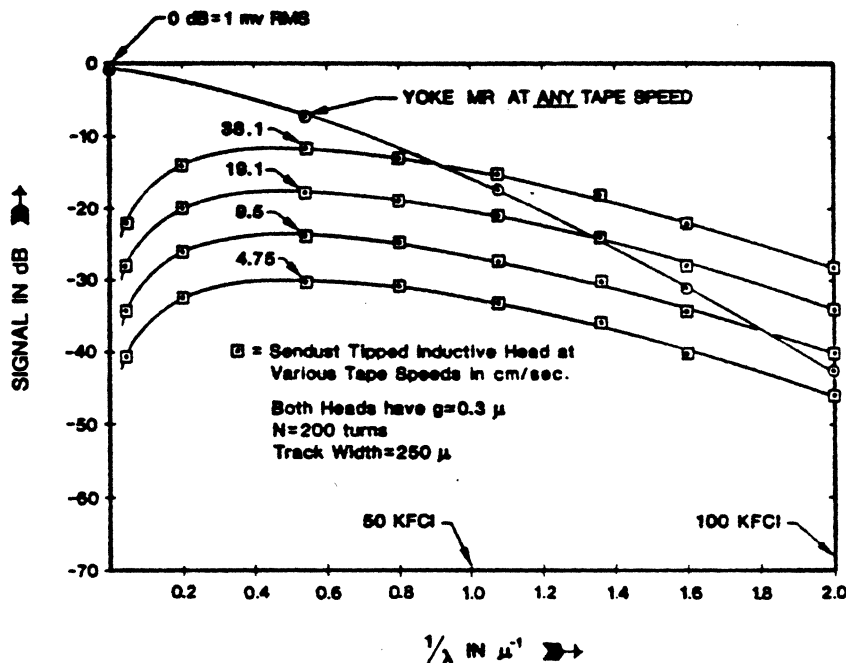


FIG. 36 YOKE MR & INDUCTIVE HEADS COMPARED

Another MR head worth noting is the recently described "over biased Hunt head" of Uchida.²⁹ Here, use is made of the fact that the demag fields are greater at the edges of the sensor element. A bias field about 4 times larger than required for optimum signal is applied. This saturates the center of the element and causes the edge of the element in contact with the medium to be optimally biased. This reduces the short wavelength signal somewhat, but reduces the long wavelength signal much more, hence, giving "improved resolution" and a smaller peak to band edge ratio, which is easier to equalize.

29. H. Uchida, IEEE Trans. on Mag., Vol. Mag. 18, 1982, pg. 1152.

MR heads have been combined with inductive thin-film record heads to form a complete read/write structure.³⁰

Head Noise

There are many sources of noise in magnetic recording other than head noise, including record and reproduce crosstalk, signal modulation noise, overwrite, flutter and wow, and dropouts. The minimum tape noise is bulk erased noise and it is easy to measure. The goal of the head designer is to cause the head noise to be less than the bulk erased noise, so that it does not affect the signal to noise ratio. The head is then said to give "tape noise limited performance."

The primary sources of inductive head noise are amplifier voltage noise E_v , amplifier current noise E_c and head resistance noise E_r . E_v and E_c for a good wide band 40 dB gain amplifier are given by

$$E_v \approx 1 \times 10^{-9} B^{1/2} \quad (21)$$

and

$$E_c \approx 1 \times 10^{-12} B^{1/2} Z. \quad (22)$$

E_r is given by

$$E_r \approx (4k T B R)^{1/2} \quad (23)$$

$$\approx 1.29 \times 10^{-10} (B R)^{1/2}.$$

B is the frequency bandwidth of concern in Hz, Z is the magnitude of the complex head impedance, k is Boltzmann's constant $k = 1.38 \times 10^{-23}$ J/°K, T is the absolute temperature $T \approx 300^\circ\text{K}$ and R is the real part of Z .

30. C. Bajorek, AIP Conf. Proc., 24, 1975, pg. 548.

Figure 37 shows the "tape stopped" electronic noise spectrum for the 200 turn head discussed earlier. The bandwidth used was $B = 3100$ Hz. Vector impedance measurements were made of the head, which gave Z and R versus frequency, and E_v , E_c and E_r were computed from equations 20, 21, and 22. The inductance was about $745\mu\text{H}$ and the dc resistance was 16Ω . These results were also plotted in Figure 37. The total expected electronic noise E_e was computed from Eq. 24 below

$$E_e = (E_v^2 + E_c^2 + E_r^2)^{1/2} \quad (24)$$

E_e is also plotted in Figure 31 and is seen to agree very well with the tape stopped noise, except at very low frequency where recombination or $1/f$ noise from the amplifier and pickup become important.

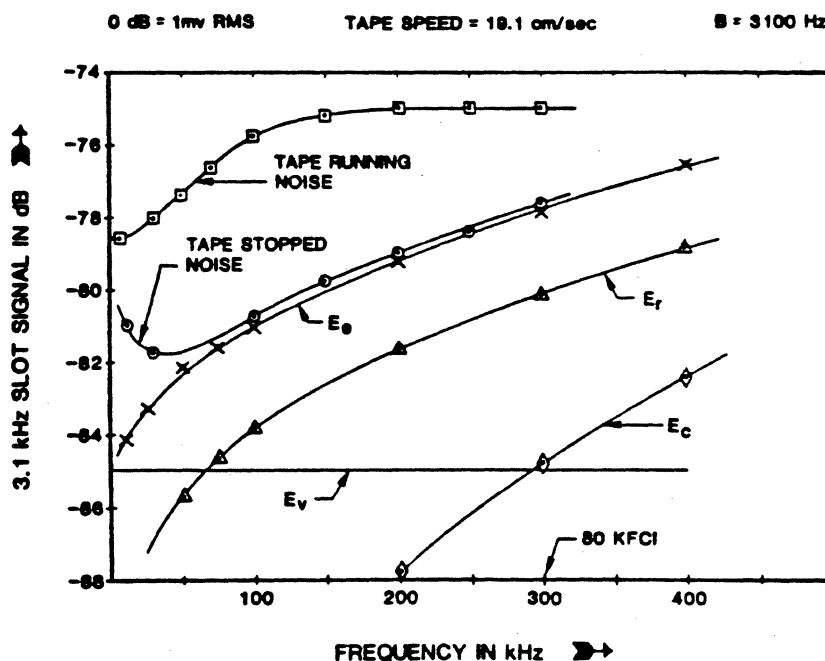


FIG. 37 INDUCTIVE HEAD NOISE SPECTRA

Er increases with frequency primarily because of "eddy current resistance" in the conductive Sendust pole tips.

Finally, the bulk erased ISOMAX tape running noise is also plotted in Figure 37. As may be seen, this head and tape make up a tape noise limited system, but with only 4 to 5 dB to spare.

Figure 38 shows the RMS to RMS, $B = 3100$ Hz slot signal to noise ratio for this Sendust tipped head and ISOMAX tape at 19.1 cm/sec tape speed. The record current was set to maximize the 80 KFCI signal.

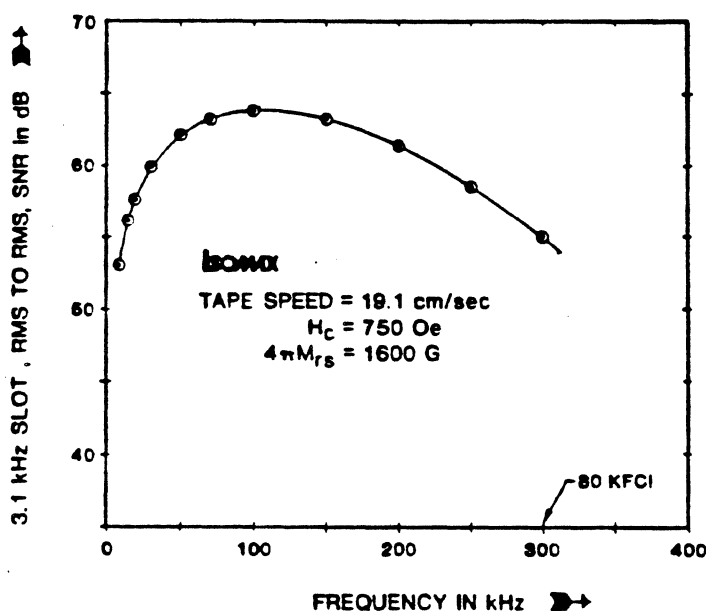


FIG. 38 3.1 kHz SLOT, RMS TO RMS, SIGNAL TO NOISE RATIO

In single crystal ferrite heads, magnetostriction noise can be a problem. The choice of crystal orientation in the head is a compromise between permeability, wear rate and magnetostriction noise. The composition of the ferrite is chosen to minimize the magnetostriction constant, but a zero value is difficult to achieve at high saturation flux density.

The MR heads generate thermal noise. The temperature coefficient of resistance is about 0.28%/°C, so a 4°C temperature excursion gives a noise spike equal to the maximum signal of 1%. At 10^7 amps/cm², the sensor may be 30°C hotter than room temperature and the moving medium serves as a heat sink. Intermittent contact between head and medium, caused by poor medium surface smoothness or dust particles, causes thermal noise spikes as the element temperature goes up momentarily. This noise source is mostly confined to lower frequencies. Another source of thermal noise is frictional heating caused by hard dust or tape particles being dragged over the head surface. This is the dominate thermal noise at frequencies above the audio range. Even this noise source is confined to frequencies below about 250 KHz with a sapphire substrate.

Magnetostriction can also be a problem with MR heads. For these reasons, it is best to use a substrate like sapphire, which is very hard and which also has a high thermal conductivity to minimize thermal noise.

Barkhausen noise and even order distortion associated with high flux levels in the MR layer can be a problem in some applications. Magnetic feedback has been used to reduce the flux level in the Yoke MR element.³¹

Several techniques have been developed to solve these and other MR head problems. See references 21 and 22 and others contained there. Figures 39 and 40 summarize MR head noise sources.

FIG. 39 MR HEAD NOISE

a) THERMAL $\frac{d\rho}{dT} \approx 0.28\%/^{\circ}\text{C}$

$$\Delta T = 4^{\circ}\text{C} \rightarrow 1.2\% \Delta \rho = \text{Max signal}$$

Hard asperities sticking out of moving media surface cause frictional heating. Important below 200 KHz.

→ Need high thermal conductivity substrate like sapphire.

b) MAGNETO STRICTIVE

$$\Delta H_k \propto \lambda \Delta S$$

magnetostriction constant strain

$$\text{So... } \Delta S \rightarrow \Delta H_k \rightarrow \Delta \sigma \rightarrow \Delta \rho \rightarrow \text{noise.}$$

→ Need $\lambda \rightarrow 0$ (81/19 NiFe)

→ Need hard substrate like sapphire.

c) PIEZO RESISTIVE

$$R = \frac{\rho l}{A} \quad \text{so... } \Delta S \rightarrow \frac{\Delta l}{\Delta A} \rightarrow \Delta R \rightarrow \text{noise.}$$

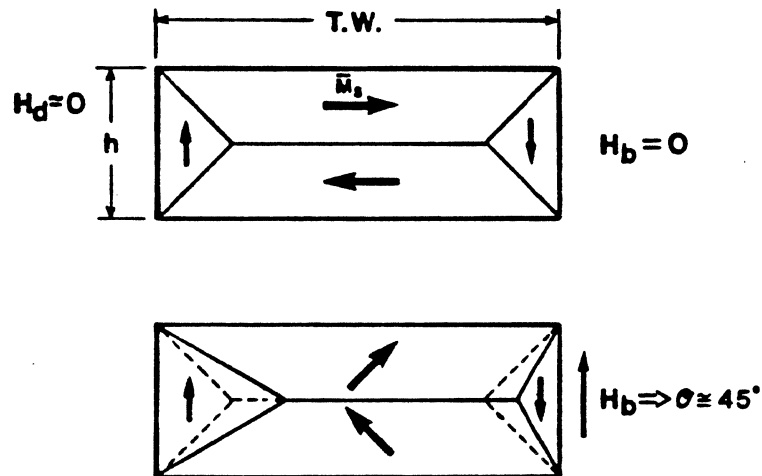
Need hard substrate.

31. E. d Niet, IEEE Trans. on Mag., Vol. Mag. 15, No. 6, Nov. 1975, pg. 1625.

FIG. 40 (MR Head Noise Cont)

d) BARKHAUSEN NOISE

Narrow T.W. $\Rightarrow$ Large $H_d \Rightarrow$ Domain Walls.



Large signal fields move domain walls at ends which "snap" over pinholes etc.

$\Rightarrow$ Barkhausen Noise

Generally not a problem for T.W. $\geq 50\mu$, $h \approx 5\mu$, $t \approx 700 \text{ \AA}$. Record Current set to max 80 KFCI $\Rightarrow$ Small Fields and contacts cover closure domains.

If approach bias point from high field side domain walls are mostly suppressed.

OVERWRITE AS A FUNCTION OF RECORD GAP LENGTH - A NEW EFFECT

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Introduction

In floppy-disk recorders a common head is used for both recording and reproducing. Because of timing constraints, old data are not erased, but instead, new data are recorded over the old data. This process results in only partial erasure of the old data, which appear as noise in the new data signal. A worst-case measure of this is "overwrite", defined as the ratio of an original 1F (or half-band-edge signal) to that remaining after being overwritten with a 2F (or band-edge signal). Overwrite of 30 dB is considered adequate for proper performance.

To avoid the reproduce gap null, and so obtain a more constant peak-to-peak signal level over the range of densities to be reproduced, the head gap length is generally chosen to be less than about half of the 2F flux change length (FCL). A 2F signal/1F signal "resolution" of at least 70% is typically required.

Generally, the record currents that give the maximum 2F signal, acceptable resolution, and 30 dB of overwrite differ in magnitude unless the recording layer is thinner than half the 2F FCL. At linear densities of 10-15 KFCI, media less than about 1 μm thick are required. This thickness corresponds to only two or three typical magnetic particle lengths. It seems unlikely that significantly thinner particulate coatings are practical. This is one of the reasons for current interest in the very thin metallic media.

It is possible to solve the overwrite problem while using thick media. The data below show that the maximum 2F signal and overwrite of 32-40 dB can be achieved simultaneously on a 5 μm thick particulate layer, even at linear densities as high as 100 KFCI, if the record gap is roughly equal to the 2F FCL. The reduction in resolution associated with this increase in gap length can be recovered with a compensating reproduce amplifier.

Experimental Results

Overwrite spectra for several record gaps were measured over a range of linear densities by using an experimental Kodak tape and a linear tape transport. Similar results were obtained with 3M 265 tape. The same 0.25 μm gap reproduce head was used throughout. The square-wave record current was set to maximize the 2F density signal in each case.

Figure 1 shows the overwrite obtained for each record gap plotted versus the 2F density. Figure 2 shows the same data plotted versus the record gap divided by the 2F FCL. Clearly all of the curves are modulated by the same resonance phenomenon. Figure 3 shows the 30 KFCI or 2F signal and overwrite plotted versus record current for the 0.86 μm or 34 μ inch gap head. Here, where $g \approx \text{FCL}$, maximum 2F signal and maximum overwrite occur at the same record current.

A possible explanation is as follows. The high-coercivity fraction of the particles in the tape are recorded first at the leading edge of the gap by the local peak in the head field and the fringing field of the approaching

3. Recording
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Variation of 2F signal and overwrite with record gap length.
 Digest For 85 InterMag

1F transition.^{1,2} If the gap is equal to one FCL, when the element of tape reaches the trailing edge of the gap, the record current is reversed and the 1F signal recorded at the leading edge is cancelled, giving maximum overwrite.

Using a gap this large will reduce the 2F signal about 4 dB because of more reproduce gap null, but this signal loss and the attendant phase distortion are linear and can be recovered with a compensating reproduce amplifier.³

Conclusion

The data presented show that, for contact recording, overwrite exceeding 32 dB and maximum band-edge signal can be achieved at densities as high as 100 KFCI on thick media if the record gap is equal to the 2F FCL.

References

1. J. Woodward et al., J. Audio Eng. Soc., Vol. 9, No. 4, p. 255, 1961.
2. R. Fayling et al., IEEE Trans. Magn., Vol. Mag.-20, No. 5, p. 718, Sept. 1984.
3. D. Tjaden, IEEE Trans. Magn., Vol. Mag.-9, p. 331, 1973.

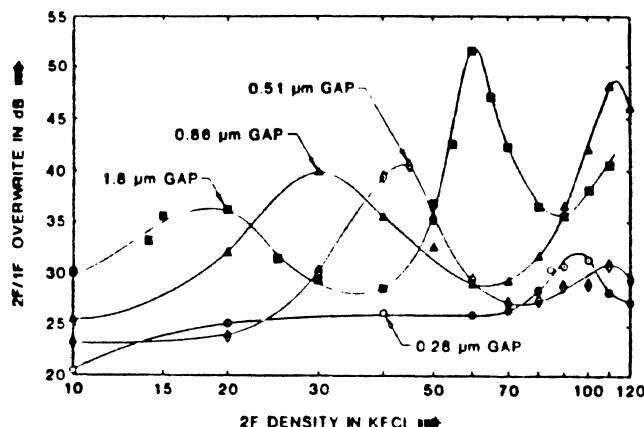


Figure 1. 2F/1F Overwrite plotted versus 2F linear density for four record gaps.

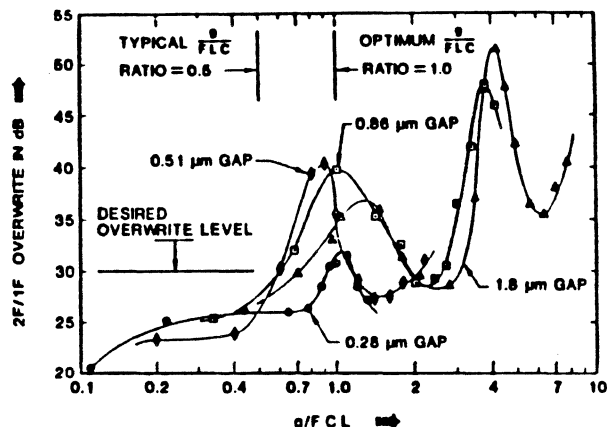


Figure 2. Overwrite plotted versus g/FCL for four record gaps.

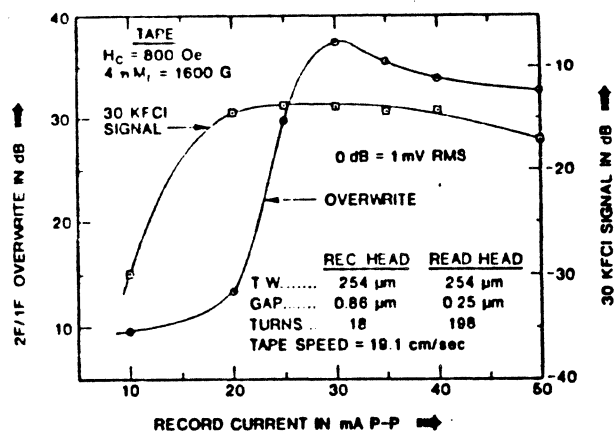


Figure 3. Overwrite and 30 KFCI signal plotted versus record current for a 0.86 μm or 34 μinch record gap.

Analog Recording Systems and Noise
John Mallinson, UCSD
Center for Magnetic Recording Research

NOISE IN ANALOG RECORDING SYSTEMS

THE PHYSICAL ORIGINS OF TAPE, HEAD AND ELECTRONICS NOISE WILL BE REVIEWED. EXPRESSIONS FOR THE NARROW-BAND AND WIDE-BAND SIGNAL TO TAPE NOISE RATIOS WILL BE DISCUSSED. COMPARISONS WILL BE MADE BETWEEN THE THEORETICAL AND ACTUAL SIGNAL TO NOISE RATIOS OF AUDIO AND INSTRUMENTATION DIRECT RECORDERS, VIDEO FREQUENCY MODULATED AND PULSE CODE MODULATED RECORDERS.

5-2

NOISE IN ANALOG RECORDING SYSTEMS

JOHN MALLINSON

DISTINCTION BETWEEN:

INTERFERENCE

**CROSS-TALK
INCOMPLETE ERASURE
FEED THROUGH
60 Hz, ETC.**

DISTORTION

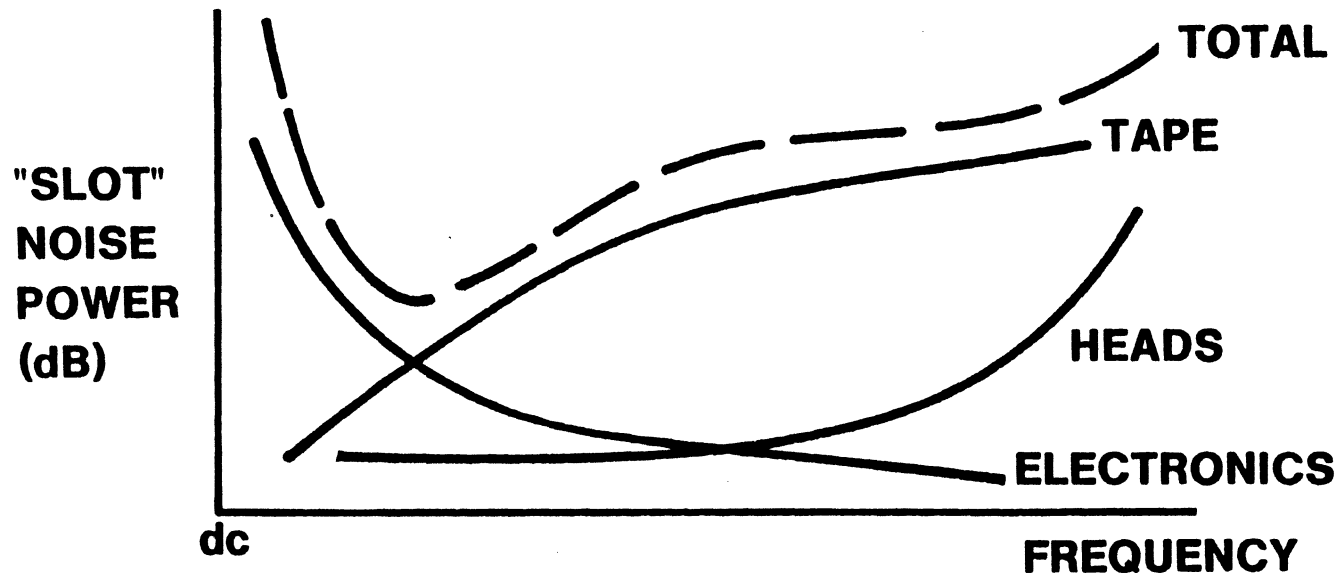
**AMPLITUDE SPECTRUM
NOT FLAT

PHASE SPECTRUM
NOT LINEAR**

NOISE

**ELECTRONICS
HEADS
TAPE/DISC**

THREE MAIN SOURCES OF NOISE



**ORIGIN OF NOISES IS ALWAYS SOME
UNCERTAINTY ABOUT A PHENOMENON:**

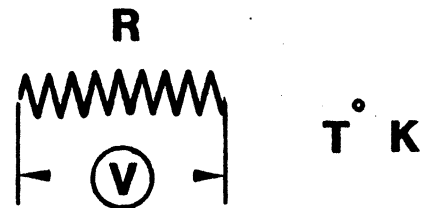
**ELECTRONICS: ELECTRON (NOISE) STATISTICS IN FIRST
STAGE REPRODUCE PRE-AMPLIFIER**

RESISTORS: ELECTRON STATISTICS

HEADS: DOMAIN WALL/ANGLE STATISTICS

**TAPES: TAPE PARTICLE POSITION OR ORIENTATION
STATISTICS**

RESISTORS $\left\{ \begin{array}{l} \text{JOHNSON NOISE} \\ \text{NYQUIST THEOREM} \end{array} \right.$



$$V = \sqrt{4kTR \Delta f} \quad \text{VOLTS}$$

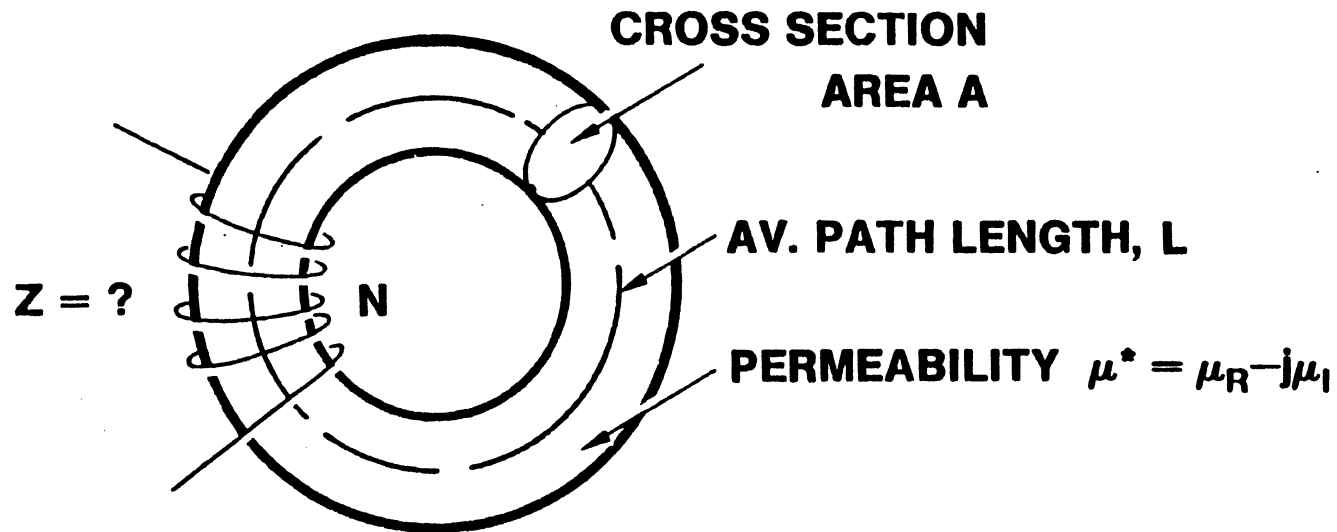
k = BOLTZMAN'S CONSTANT
(1.38 10⁻²³ JOULES/DEGREE)

T = ABSOLUTE TEMPERATURE

R = RESISTANCE IN OHMS

Δf = BANDWIDTH OF MEASUREMENT $\left(\begin{array}{l} \text{HERZ} \\ \text{CPS} \end{array} \right)$

ELECTRICAL IMPEDANCE OF A TOROID



$$\text{INDUCTANCE, } L^* = \left(0.4 \pi 10^{-8}\right) N^2 A \frac{\mu^*}{L}$$

$$\text{INDUCTANCE} = j\omega L^* \approx j\omega \frac{N^2 A}{L} \mu_R + \omega \frac{N^2 A}{L} \mu_I$$

PURE INDUCTANCE

STORES ENERGY

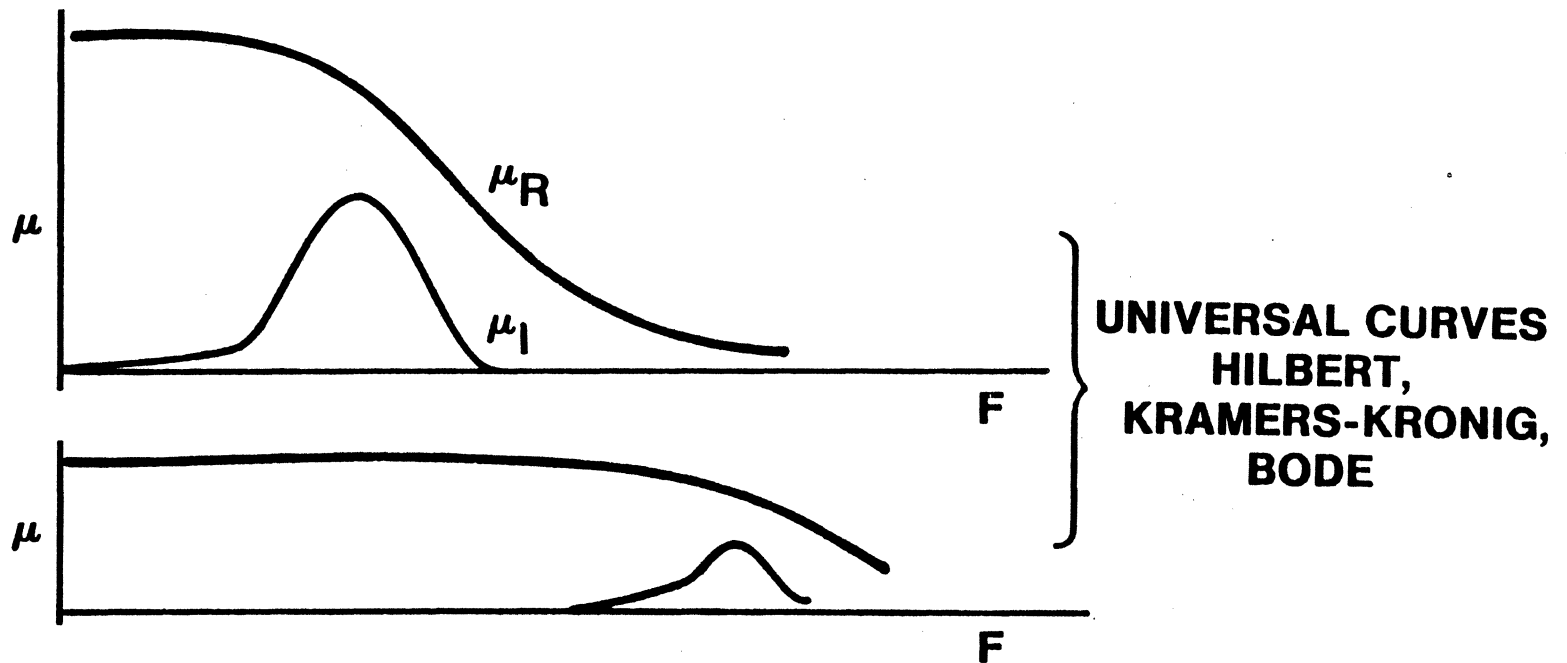
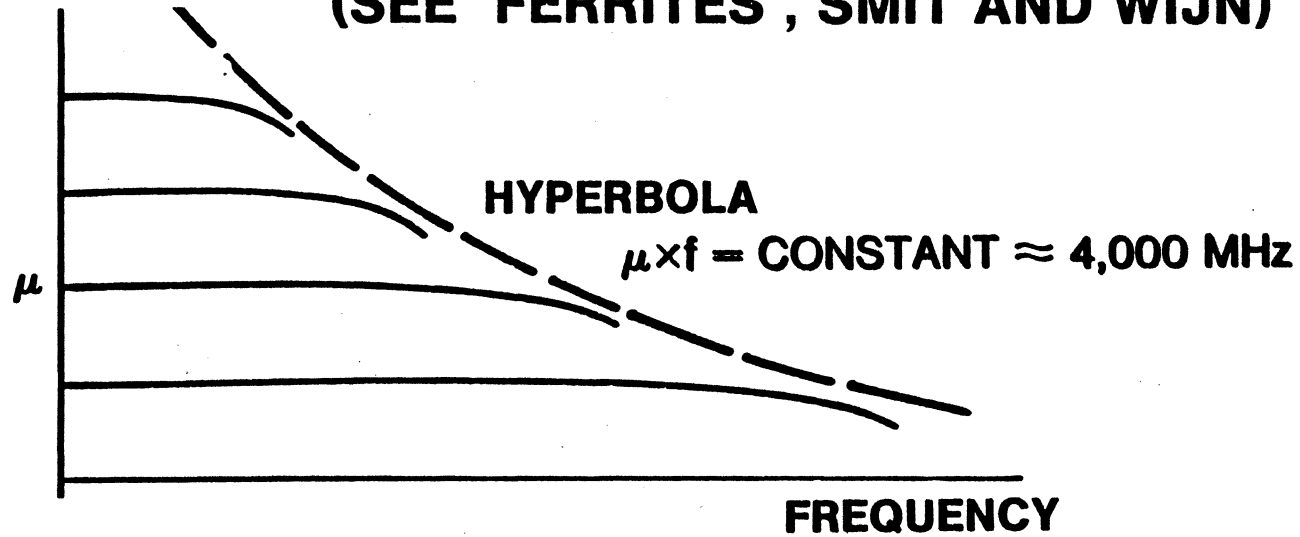
$\therefore$ NOISELESS

RESISTANCE

DISSIPATES ENERGY

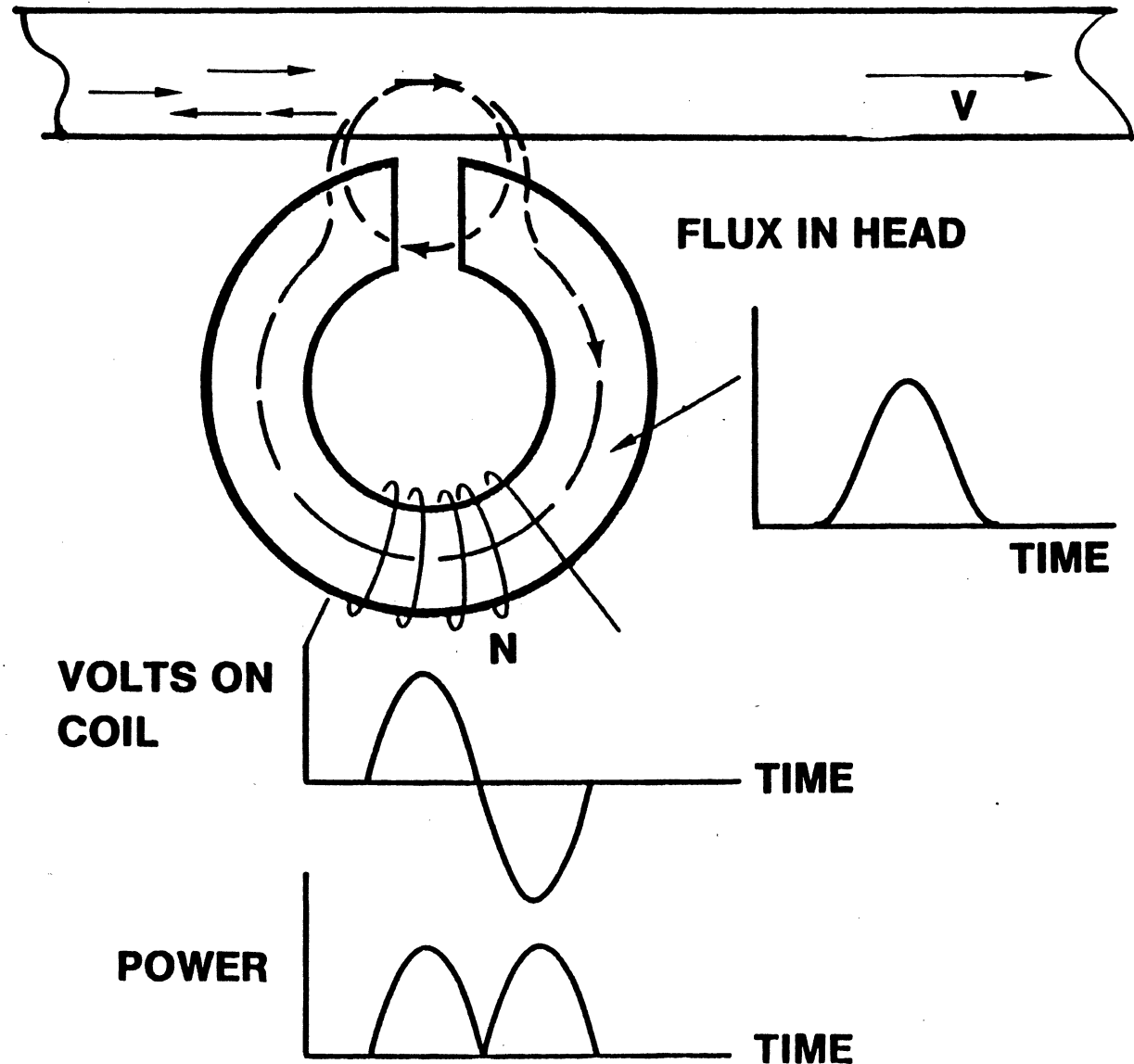
$\therefore$ NOISY

COMPLEX PERMEABILITY OF FERRITES (SEE "FERRITES", SMIT AND WIJN)



TAPE NOISE

SHOULD BE DOMINANT IN A PROPERLY
DESIGNED RECORDING SYSTEM
EACH PARTICLE PRODUCES A PULSE OF POWER



IF PARTICLE:

POSITIONS ARE RANDOM

DIRECTIONS OF MAGNETIZATION ARE RANDOM

**THEN, TO FIND THE TOTAL NOISE POWER, WE
SIMPLY ADD THE POWERS**

IF E_1 AND E_2 ARE TWO SIGNALS,

$$\overline{(E_1 + E_2)^2} = \overline{E_1^2} + \overline{E_2^2} + 2\overline{E_1 E_2}$$

IF E_1 AND E_2 ARE RANDOM $\overline{E_1 E_2} = 0$

**UNCORRELATED
INCOHERENT**

**THE NOISE POWER IS THE SUM OF THE SQUARES
(NOT THE SQUARE OF THE SUM)**

**TOTAL TAPE NOISE POWER
(FROM AN UNEQUALIZED SYSTEM)
(See "Physics of Recording, MEE)**

$$P = \int_{-\infty}^{\infty} E_N^2(k) dk = 4\pi\mu^2 n W V^2 \left\{ \frac{d(a + \frac{d}{2})}{a^2(a+d)^2} \right\}$$

WHERE:

$E_N^2(k)$ = NOISE POWER DENSITY,

k = WAVENUMBER $\left(\frac{2\pi}{\lambda} \right)$,

μ = PARTICLE MAGNETIC MOMENT,

n = NO. OF PARTICLES/UNIT VOLUME,

W = TRACK WIDTH,

V = HEAD/TAPE VELOCITY,

d = COATING THICKNESSES,

a = HEAD/TAPE SPACING

TOTAL TAPE NOISE POWER (Continued)

NOTE THAT THE TOTAL NOISE POWER:

- 1) INCREASES WITH μ ($=M_s \times \text{VOL}$)
 - 2) INCREASES WITH n
 - 3) INCREASES WITH W
 - 4) INCREASES WITH V^2
 - 5) DECREASES WITH a
 - 6) ALMOST INDEPENDENT OF d
- DIFFERENCE BETWEEN
COHERENT AND INCOHERENT

**KNOWING THE TOTAL NOISE POWER DOES NOT
GIVE US THE NOISE POWER DENSITY, $E^2(k)$.**

THE NOISE POWER DENSITY OR SPECTRUM

$$\text{NPS}(k) = E_N^2(k)$$

$$= 4\pi\mu^2 n W V^2 k (1 - e^{-2kd}) e^{-2ka} \Delta k$$

NOTE THAT:

1) INCREASES WITH μ

2) INCREASES WITH n

3) INCREASES WITH W

4) INCREASES WITH V^2

5) INCREASES WITH $k = \frac{2\pi}{\lambda}$

6) INCREASES WITH d

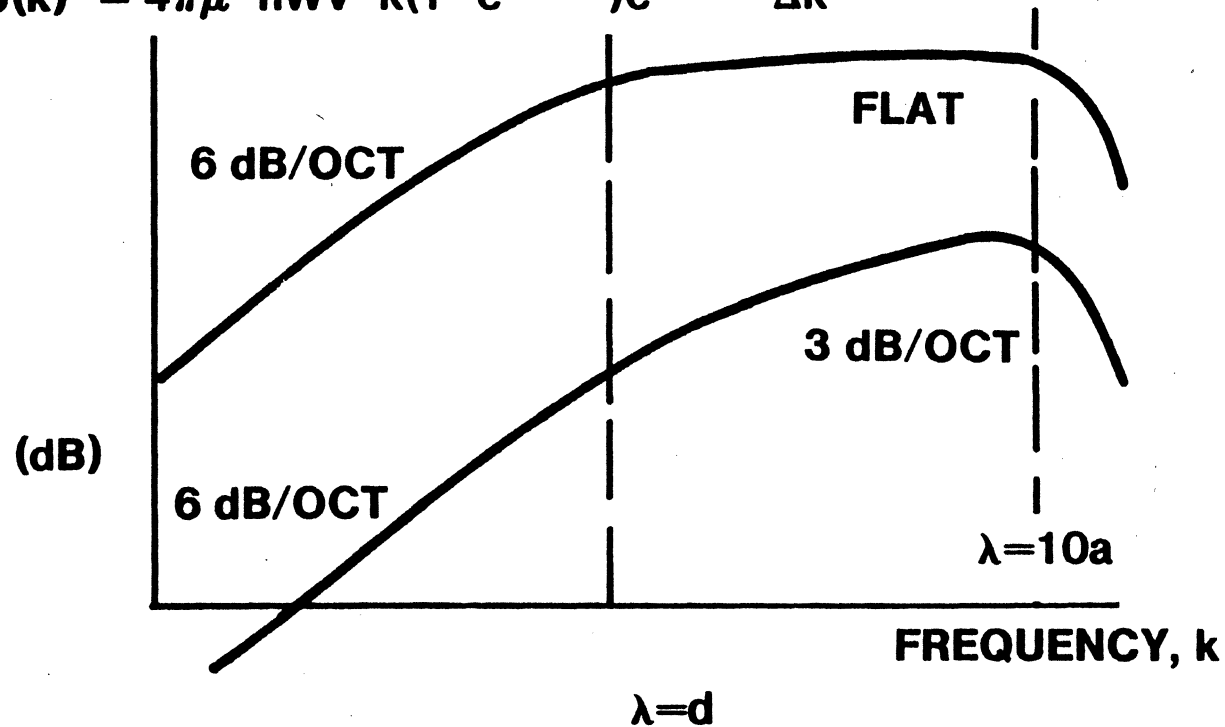
7) DECREASES WITH a

COMPARE NPS(k) WITH THE WALLACE SPECTRUM FOR THE COHERENT SIGNAL

$$\text{SPS}(k) = \frac{1}{4} \left[4\pi\mu nWV(1-e^{-kd})e^{-ka} \right]^2$$

MEAN SQUARE OF SINE WAVE = $\frac{1}{2}$, (TWO SIDED SPECTRA)

$$\text{NPS}(k) = 4\pi\mu^2 nWV^2 k(1-e^{-2kd})e^{-2ka} \Delta k$$



NARROW BAND OR SLOT SIGNAL TO NOISE RATIO

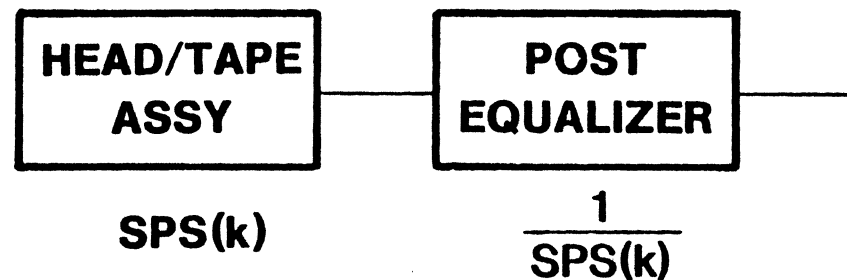
$$\begin{aligned}\text{SNR SLOT} &= \frac{\text{SPS}(k)}{\text{NPS}(k)} \\ &= \pi \frac{nW(1-e^{-kd})^2}{k(1-e^{-2kd})}\end{aligned}$$

NOTE THAT:

- 1) INDEPENDENT OF μ**
- 2) INDEPENDENT OF V**
- 3) INDEPENDENT OF a**
- 4) INCREASES WITH n**
- 5) INCREASES WITH W**
- 6) DECREASES WITH kd**
- 7) DECREASES WITH k**

**IN ORDER TO HAVE A DISTORTION LESS SYSTEM
THE OUTPUT MUST BE "EQUALIZED"**

**THE REQUIRED EQUALIZATION IS JUST THE
RECIPROCAL OF THE WALLACE SPECTRUM**



OVERALL TRANSFER FUNCTION IS

$$SPS(k) \cdot \frac{1}{SPS(k)} = 1$$

WIDEBAND SIGNAL TO NOISE RATIO

$$\text{SNR}_{\text{WIDE}} = \left[\int_{k_{\min}}^{k_{\max}} \frac{k(1-e^{-2kd}) dk}{\pi n W (1-e^{-kd})^2} \right]^{-1}$$

$$= \pi n W W \left[\int_{k_{\min}}^{k_{\max}} k \coth \frac{kd}{2} dk \right]^{-1}$$

$$\approx 2\pi n W \left[k_{\max}^2 - k_{\min}^2 \right]^{-1}$$

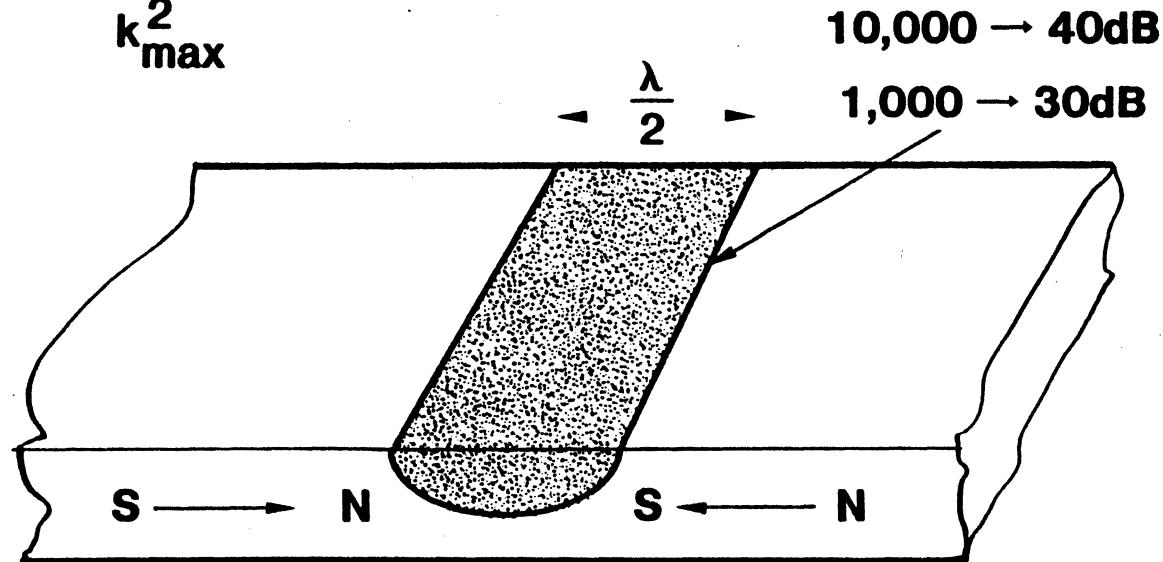
($kd \gg 1$)

HIGH DENSITY SYSTEMS

$$\approx 2\pi n W k_{\max}^{-2} = \frac{n W \lambda_{\min}^2}{2\pi}$$

WHY IS IT THAT:

$$\text{SNR} \propto \frac{nW}{k_{\max}^2} \propto nW\lambda_{\min}^2 \quad ???$$



THE REPRODUCE HEAD ONLY SENSES A VOLUME OF TAPE, $1/2$ A WAVELENGTH LONG AND ABOUT $1/5 \lambda$ DEEP, AND THE TRACKWIDTH WIDE:

$$\text{VOLUME} \propto W\lambda^2$$

$\therefore$ ALWAYS BETTER TO REDUCE W THAN REDUCE λ !!

COMPARISONS WITH REALITY

A PROFESSIONAL AUDIO RECORDER

A.C. BIAS	- 1% THIRD HARMONIC DISTORTION LEVEL - ABOUT 20% OF MAXIMUM SIGNAL
BANDWIDTH SPEED	40 Hz-15 kHz 7.5 INCH/SECOND
TRACKWIDTH n ($\gamma\text{-Fe}_2\text{O}_3$)	80 mils 10^{15} PARTICLES/CUBIC INCH
	SNR_{WIDE} (FLAT EQUALIZATION).
EXACT CALC.	54 dB
APPROX CALC.	55 dB
MEASURED	56-58 dB

to good to fair (1/2 inch dia)
 and $\lambda = 6 \mu$
 $\rho = 4 \mu$ long

Superparamagnetic $\left(\frac{1}{2} \text{ (area of the)} \right) = kT$
 3/4 inch

thermally relaxing.

AN INSTRUMENTATION RECORDER (A.C. BIAS)

BANDWIDTH 400 Hz - 1.5 MHz

SPEED 120 ips

TRACKWIDTH 50 mil

n 10^{15} (STANDARD $\gamma\text{-Fe}_2\text{O}_3$)

largest λ (slightest)
 λ

(size of the head) (size of the gap)

SNR_{WIDE} (WITH Fe PARTICLES)

EXACT CALC.	36 dB	48
APPROX CALC.	36 dB	48
MEASURED	34 dB	44

Fe $1/16$ of $\gamma\text{-Fe}_2\text{O}_3$
 particle size

AN F.M. VIDEO RECORDER

IF SIGNAL $f(x) = a \cos k_s x$,
 THEN F.M. IS $\cos [k_c x + \beta \int f(x) dx]$,
 ↑ sensitivity

PEAK WAVENUMBER DEVIATION IS $a\beta$,

$$\text{AND SNR} \approx \frac{3\pi n W (a\beta)^2}{2k_c k_s^3}$$

IN TIME DOMAIN, $f = \frac{kv}{2\pi}$,

$$\text{SNR} = \frac{3n W V^2 (\Delta f)^2}{8\pi f_c f_s^3}$$

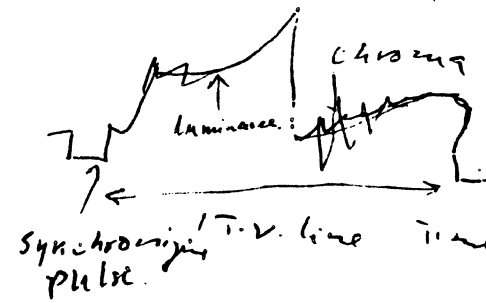
$$\text{OR SNR} = \frac{3n W V^2 m^2}{8\pi f_c f_s} \cdot \left(m = \frac{\Delta f}{f_s}\right)$$

Chassis $\lambda_{max} = 40\mu$
 VHS density = 264
 r.p.p.

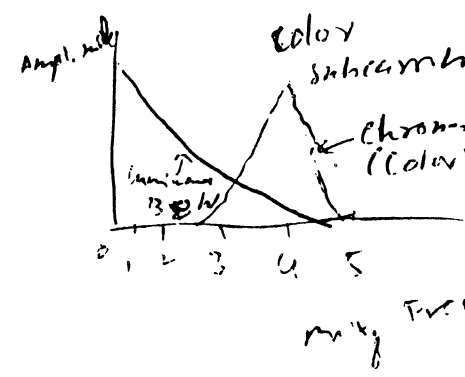
1 TV line
 (64 lines)

525 lines 3-line
 US
 national television standard
 625 lines - PAL
 phase alternating
 line system

800 lines - 10 lines
 150R



TV. intensity - AM
 → demodulated → freq. modulated
 (V. sec)



AN F.M. VIDEO RECORDER (Continued)

A TYPE "C" PROFESSIONAL MACHINE:

$$n = 10^{15} \text{ PARTICLES/CUBIC INCH}$$

$$W = 5 \cdot 10^{-3} \text{ INCHES}$$

$$V = 1000 \text{ IPS}$$

$$\Delta f = 3 \text{ MHz/VOLT VIDEO INPUT (1 VOLT PEAK)}$$

$$f_c = 9 \text{ MHz}$$

$$f_s = 4.5 \text{ MHz.}$$

$$\text{SNR} = 38 \text{ dB} \frac{\text{MEAN POWER}}{\text{MEAN POWER}} \left(\frac{\text{RMS}}{\text{RMS}} \right)$$

$$= 47 \text{ dB} \frac{\text{PEAK POWER}}{\text{MEAN POWER}} \left(\frac{\text{P-P}}{\text{RMS}} \right)$$

MEASURED VALUE IS 49-50 dB (PRE-EMPHASIS)

A PULSE CODE MODULATED SYSTEM (PCM OR "DIGITAL")

TRUE NOISE CAUSES BIT ERRORS ONLY. ERRORS IN QUANTIZATION APPEAR AS NOISE. SUPPOSE THE PEAK SIGNAL IS 1 VOLT. SUPPOSE THERE ARE N BITS/WORD. THE QUANTIZING INTERVAL IS 2^{-N} (APPROX.).

THE RMS QUANTIZING ERROR IS $\frac{2^{-N}}{\sqrt{12}} *$

$$\text{SNR} = 2^N \sqrt{12} \quad \frac{\text{PEAK SIGNAL}}{\text{RMS NOISE}}$$

$$= 2^{2N} .12 \quad \frac{\text{POWER}}{\text{POWER}}$$

$$= (6N+10.8) \quad \text{dB}$$

$$* \int_{-1/2}^{1/2} x^2 dx = 2 \left[\frac{x^3}{3} \right]_0^{1/2} = 1/12$$

REFERENCES FOR SESSIONS ANALOG SYSTEMS AND NOISE

- [1] J. C. MALLINSON "MAXIMUM SIGNAL-TO-NOISE RATIO OF A TAPE RECORDER", IEEE TRANSACTIONS ON MAGNETICS, VOL. MAG-5, NO. 3, PP. 182-186, SEPTEMBER, 1969.**
- [2] J. C. MALLINSON, "ON EXTREMELY HIGH DENSITY DIGITAL RECORDING", IEEE TRANSACTIONS ON MAGNETICS, VOL. MAG-10, NO. 2, PP. 368-373, JUNE, 1974.**
- [3] J. C. MALLINSON, "THE SIGNAL-TO-NOISE RATIO OF A FREQUENCY-MODULATED VIDEO RECORDER", E.B.U. REVIEW-TECHNICAL, NO. 153, PP. 1-4, OCTOBER, 1975.**
- [4] J. C. MALINSON, "TUTORIAL REVIEW OF MAGNETIC RECORDING", IEEE TRANSACTIONS ON MAGNETICS, VOL. 64, NO. 2, PP. 196-208, FEBRUARY, 1976.**

The Magnetic Recording Channel

**Mike Haynes
IBM Corporation**

SYMBOLSSOUNDIMAGES

DIGITS

CLAY TABLETS, PAPYRUS

TORCHES

PRINTING PRESS

SEMAPHORE

TELEGRAPH

SUBMARINE CABLE

TYPEWRITER

PUNCHED CARD

RADIO TELEGRAPH

TELEPRINTER

PUNCHED PAPER TAPE

MAGNETIC DRUM

MAGNETIC TAPE

MAGNETIC DISK

RADAR DATA TRANS.

TELEMETRY

SATELLITE DATA

OPTICAL DISK

TELEPHONE

PHONOGRAPH

MAGNETIC WIRE

RADIO TELEPHONE

MAGNETIC TAPE

PCM TELEPHONY

MULTILEVEL TRANS.

DIGITAL AUDIO

OPTICAL DISK

PHOTOGRAPH

MOTION PICTURE

MICROFILM

FACSIMILE

VIDEO PHONE

TELEVISION

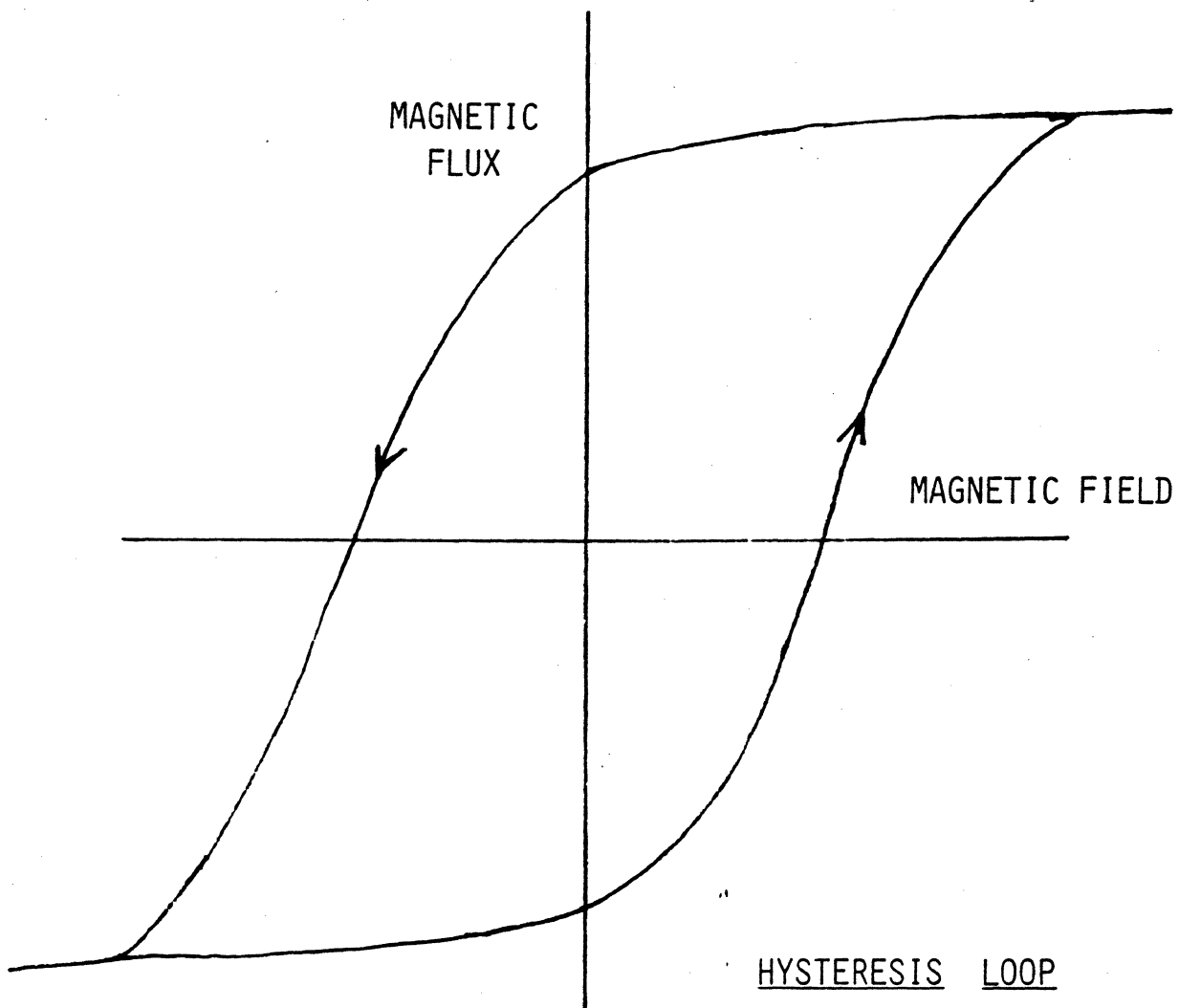
VIDEO TAPE

VIDEO DISK

DIGITAL VIDEO

MAVICA

DEVELOPMENT OF INFORMATION STORAGE AND TRANSMISSION



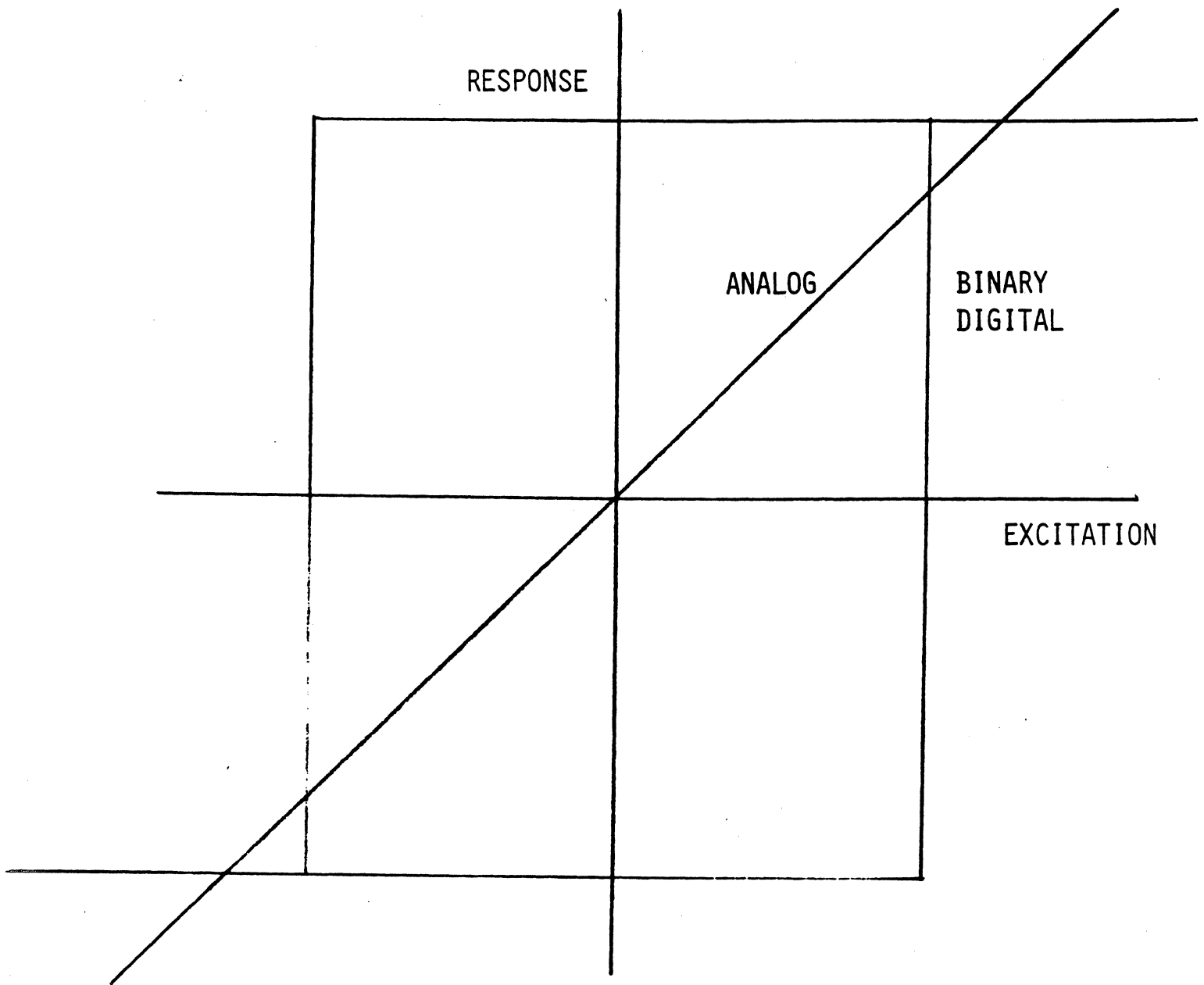
HYSTERESIS -- LAG

NON-LINEAR
SATURATION
ENERGY LOSS
TIME DEPENDENT

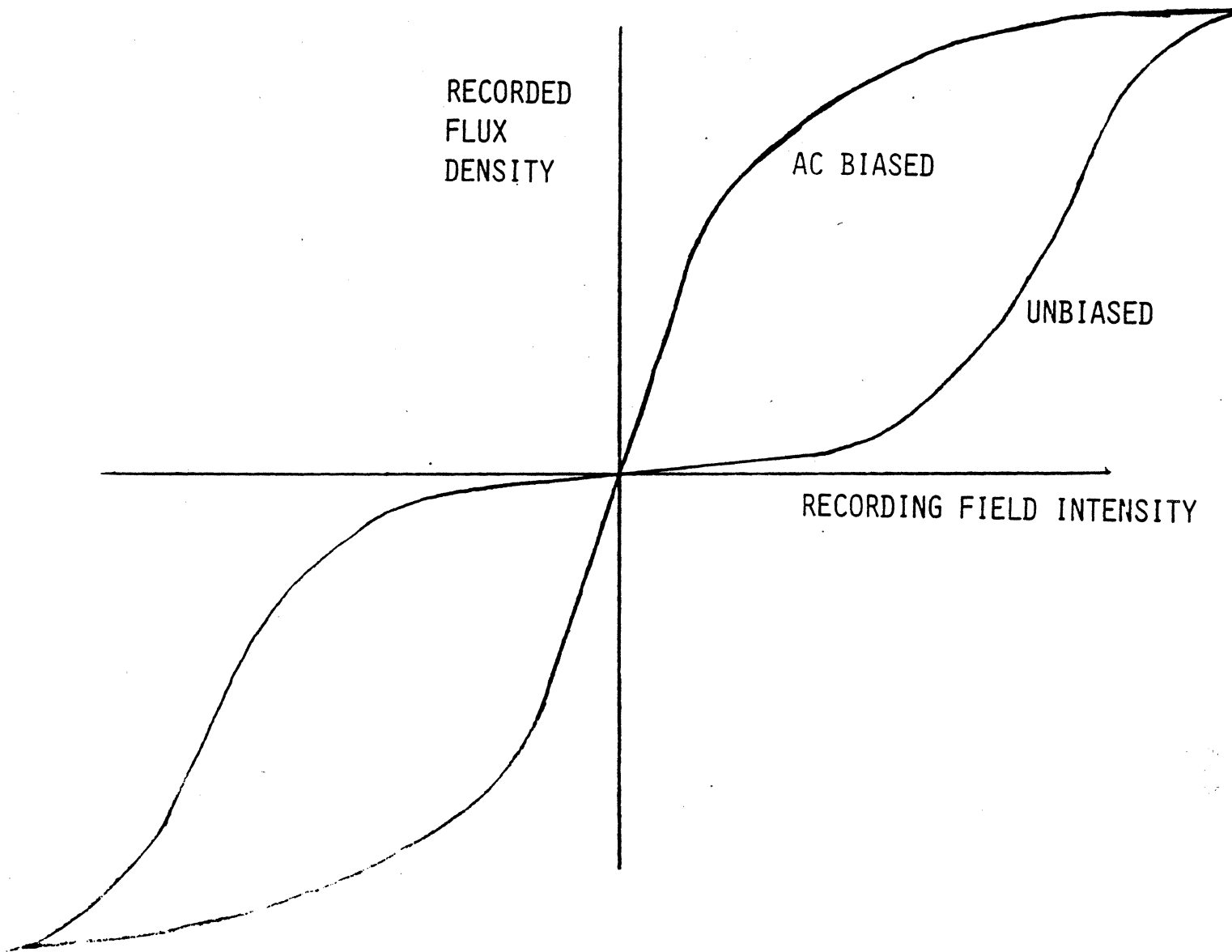
AN ESSENTIAL REQUIREMENT
FOR STORAGE-- MAGNETIC CORES

MAGNETIC RECORDING

HYSTERESIS
MECHANICAL MOTION



IDEAL TRANSFER-RESPONSE CHARACTERISTICS



MAGNETIC RECORDING CHANNEL

TRANSFER RESPONSE CHARACTERISTICS

AN 'ANALOG' CHANNEL
NONLINEARITY
SATURATION
DISTORTION
NOISE

ANALOG RECORDING

LINEARIZE

DC BIAS

AC BIAS

DIGITAL RECORDING

SATURATE *- Thin media*

TWO STATES

RECORD TRANSITIONS

QUASI-LINEAR *- Thick media*

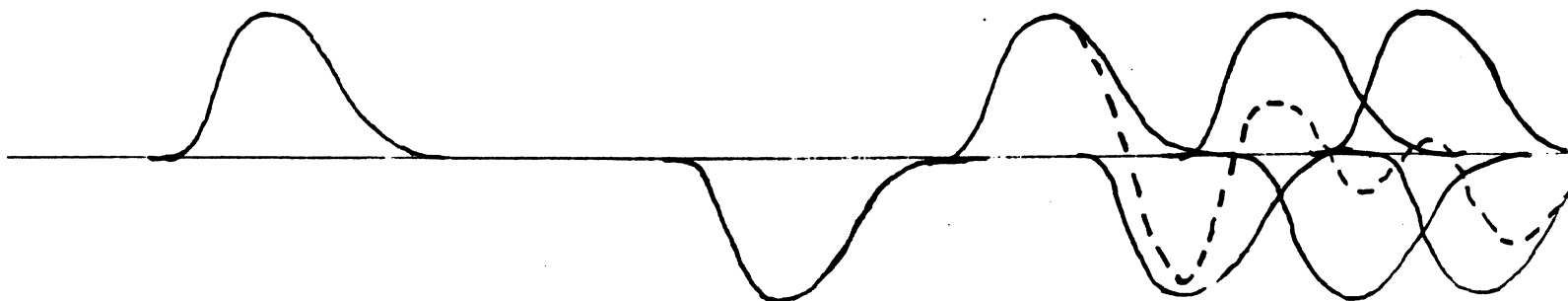
SIGNAL PROCESSING

LINEARIZE

APPLICATION STRATEGIES FOR MAGNETIC RECORDING CHANNEL



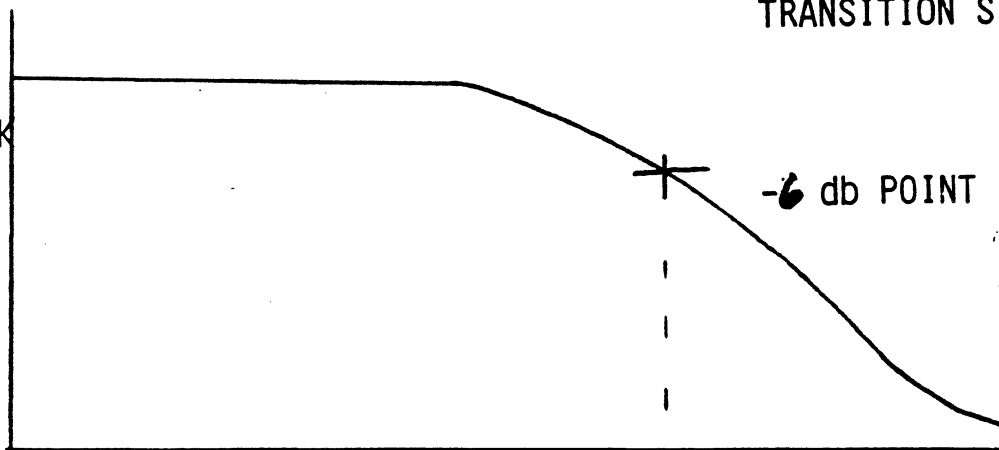
WRITE CURRENT



READ-HEAD OUTPUT VOLTAGE

SUPERPOSITION OF
TRANSITION SIGNALS

PEAK-TO-PEAK
OUTPUT
VOLTAGE

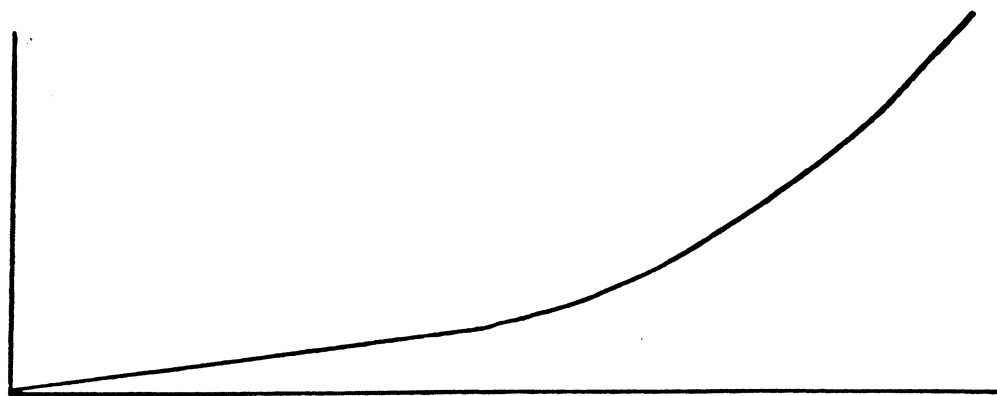


-6 db POINT

Handwritten note:
at 1252
input
output

RECORDING DENSITY (TRANSITIONS PER INCH)

PEAK-SHIFT



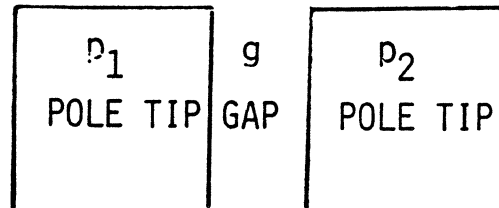
RECORDING DENSITY

SUBSTRATE

MAGNETIC COATING

th -- THICKNESS

d -- SEPARATION



RECORDING DENSITY LIMITERS IN SATURATION RECORDING

MEDIA THICKNESS

SEPARATION

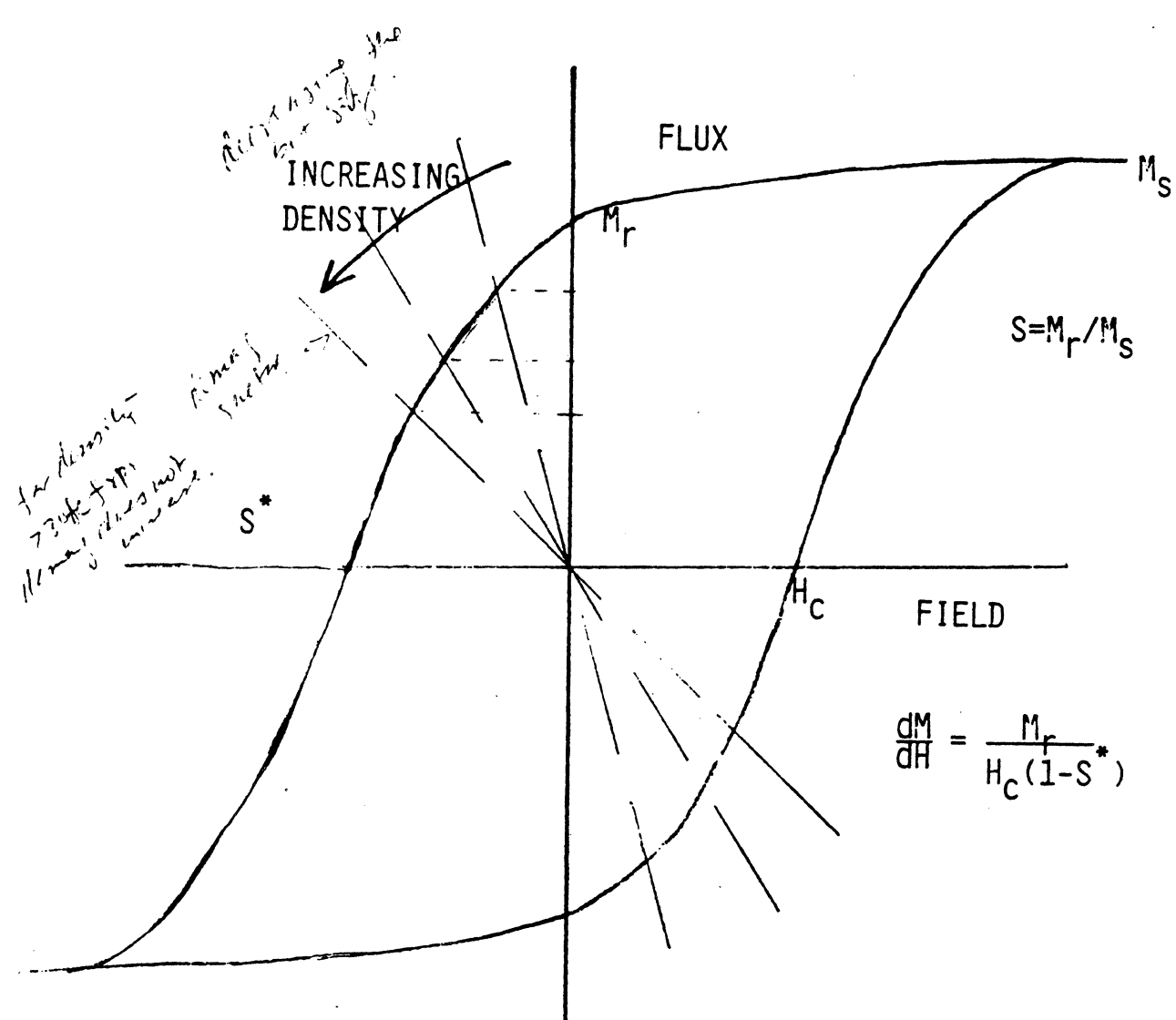
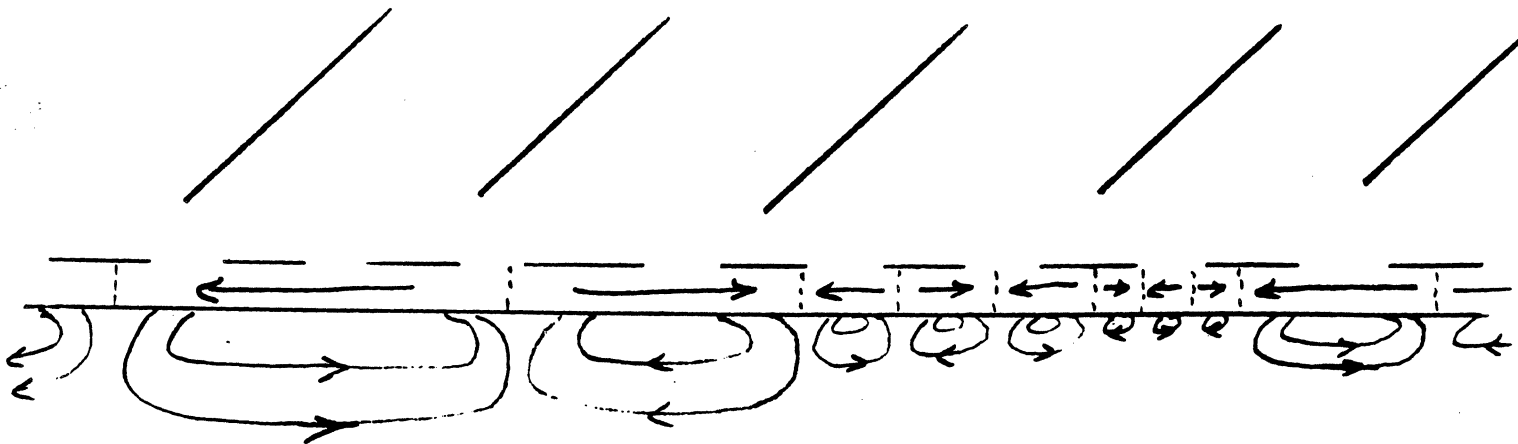
GAP LENGTH

POLE TIP LENGTH

TRANSITION LENGTH

DEMAGNETIZATION

WRITE FIELD GRADIENT



$$\frac{dM}{dH} = \frac{M_r}{H_c(1-S^*)}$$

RECORDING DEMAGNETIZATION

SATURATION-RECORDING ANALYSIS

THIN MEDIA

SELF-CONSISTENT FIELD CALCULATIONS

ARCTANGENT TRANSITION SHAPE

$$M_x = \frac{2M_0}{\pi} \arctan x/a, \quad a = \text{transition length}$$

LORENTZIAN PULSE RESPONSE

$$e(t) = \frac{1}{1 + (2t/PW_{50})^2}$$

PULSE WIDTH, $PW_{50} = \frac{1}{(g^2 + 4(d+a)(d+a+th))^{1/2}}$

QUASI-LINEAR ANALYSIS

THICK MEDIA

SUBSTRATE CHARACTERISTICS

NON-SATURATE RECORDING

"PREFERRED DEPTH", UNBIASED OR AC BIAS

FREQUENCY-DOMAIN MEASUREMENT AND ANALYSIS

LINEAR ANALYSIS, FOURIER TRANSFORMS

DATA TRANSMISSION THEORY

EQUALIZATION, OPTIMIZATION

R.O. McCary, "Saturation Magnetic Recording Process,"
IEEE Trans. Mag. V. MAG-7, March 1971, pp4-16.

B.K. Middleton and P.L. Wisely, "Pulse Superposition
and High-Density Recording," IEEE Trans. Mag.,
V. MAG-14, Sept. 1978, pp 1043-50.

unif. slope

*flexible media
changes slope & size with
humidity & temp
→ bias & TPI*

CATEGORIES OF SIGNAL DISTORTION

LINEAR

FREQUENCY DISTORTION

AMPLITUDE AND PHASE VARIATION VS FREQUENCY

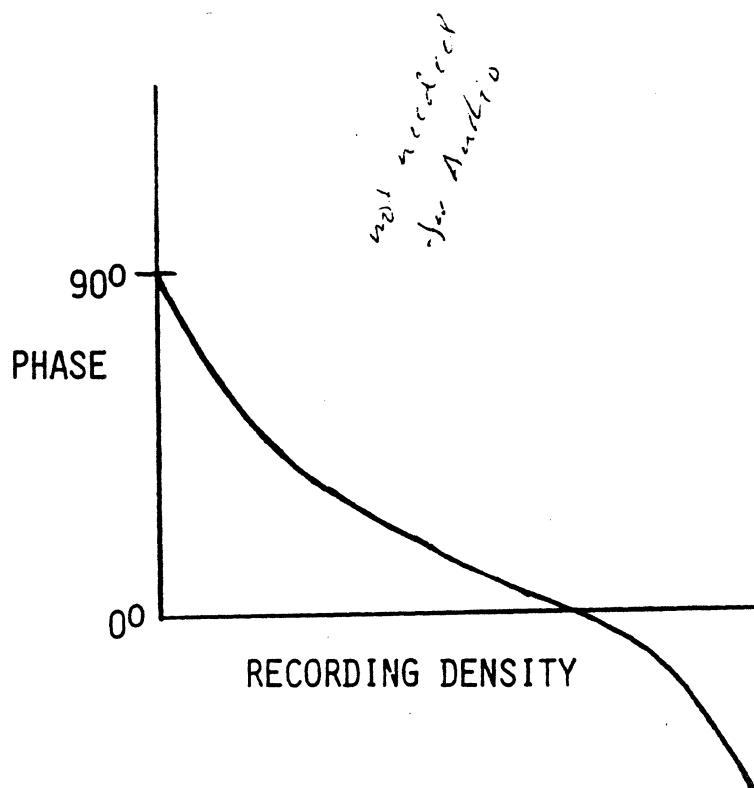
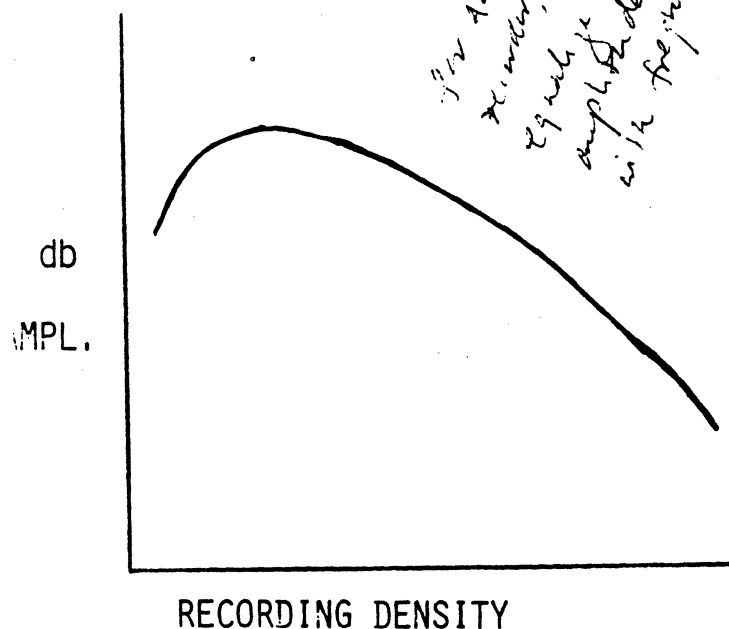
NONLINEAR, NO MEMORY EFFECTS

HARMONIC DISTORTION

INTERMODULATION DISTORTION

NONLINEAR WITH MEMORY

NONLINEAR INTERSYMBOL INTERFERENCE



FREQUENCY DISTORTION

WALLACE'S EQUATIONS

SEPARATION

GAP

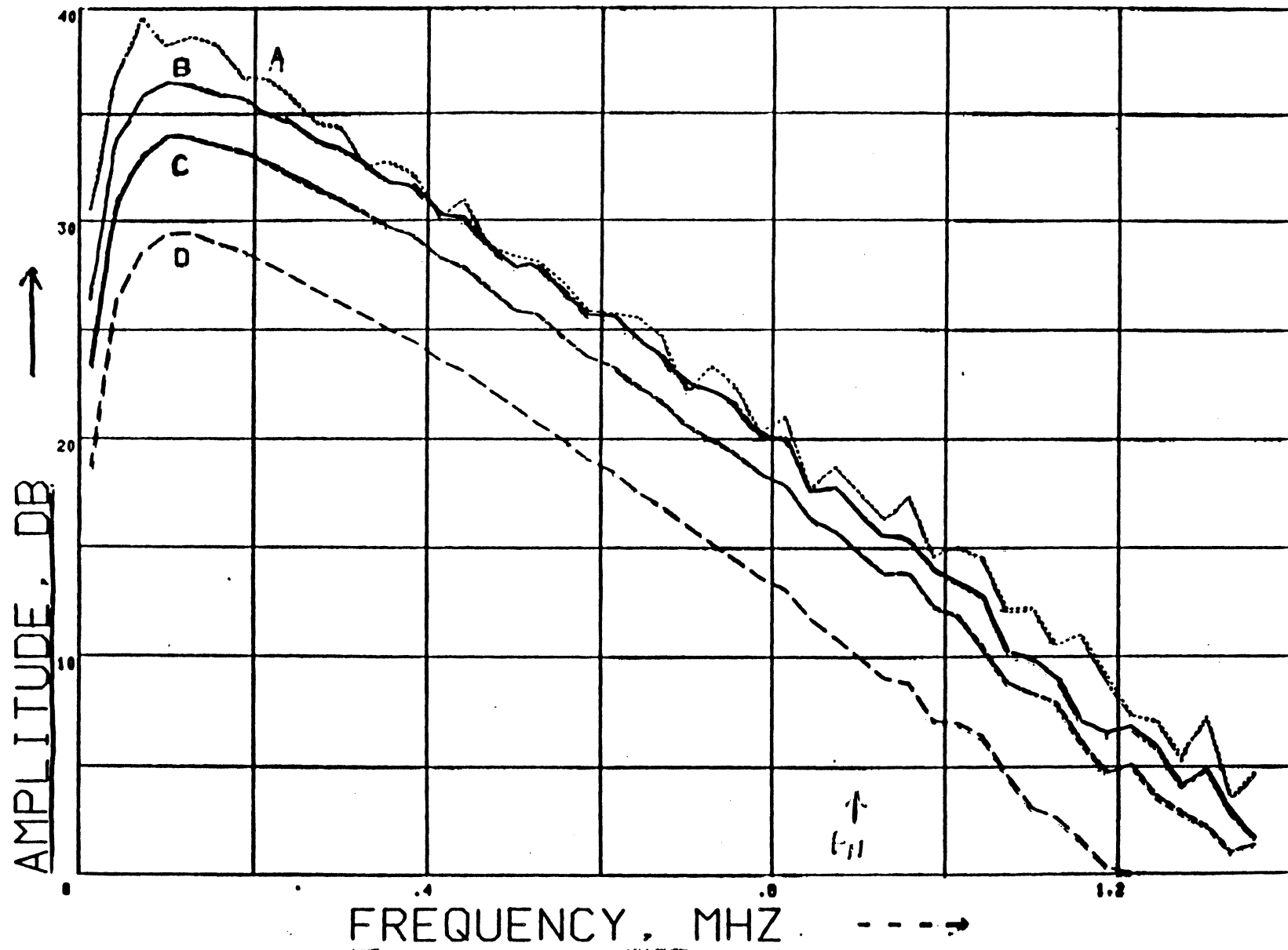
THICKNESS

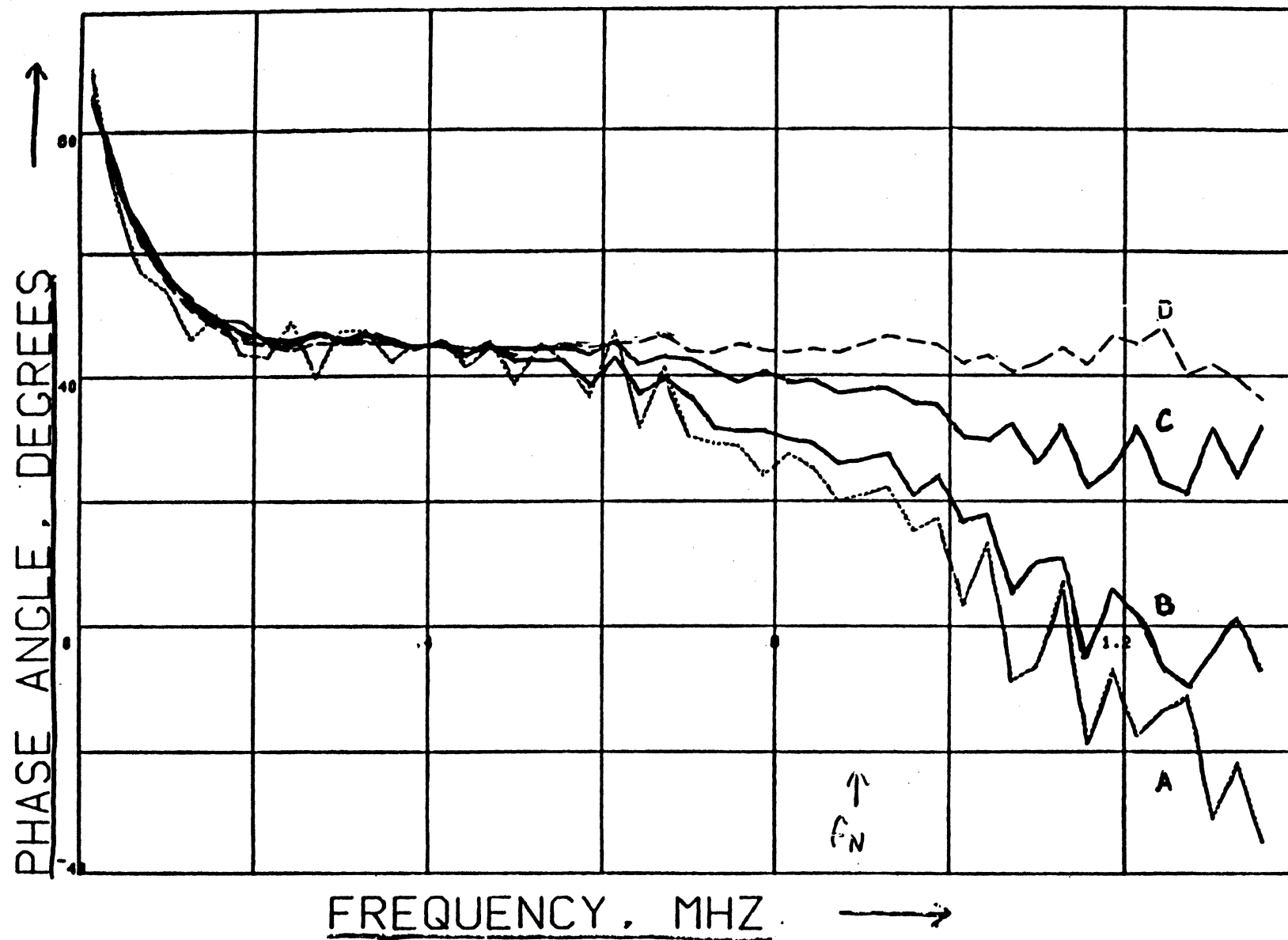
PHASE EFFECT DURING RECORDING

LINEAR EFFECTS

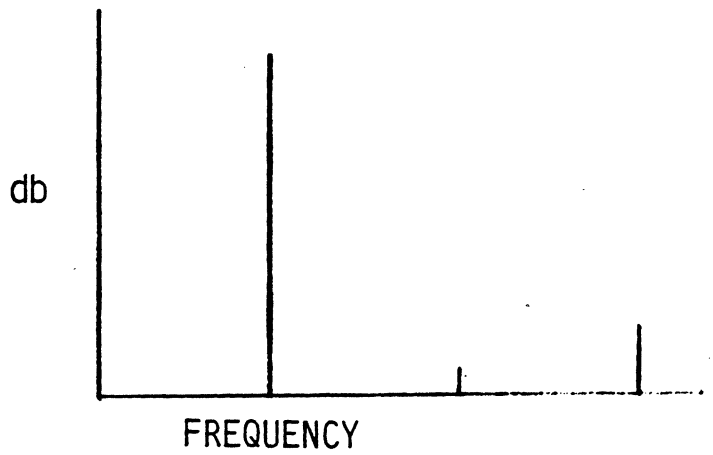
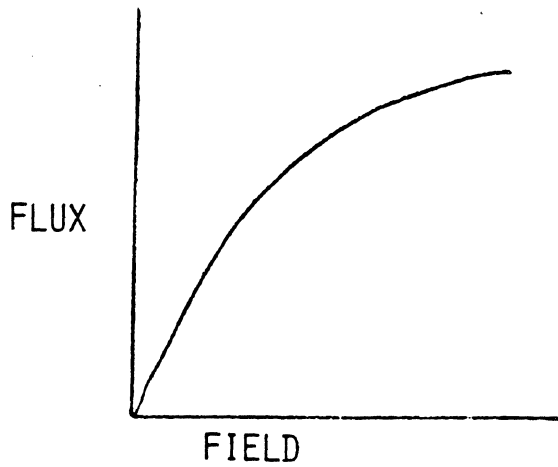
CORRECTABLE BY EQUALIZATION

M.K. Haynes, "Experimental Determination of the Loss and Phase Transfer Functions of a Magnetic Recording Channel," IEEE Trans. Mag. V. MAG-13, Sept. 1977, pp1284-86.

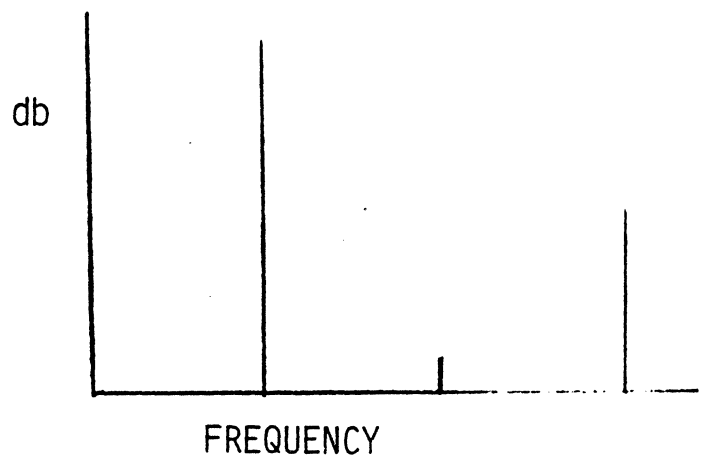
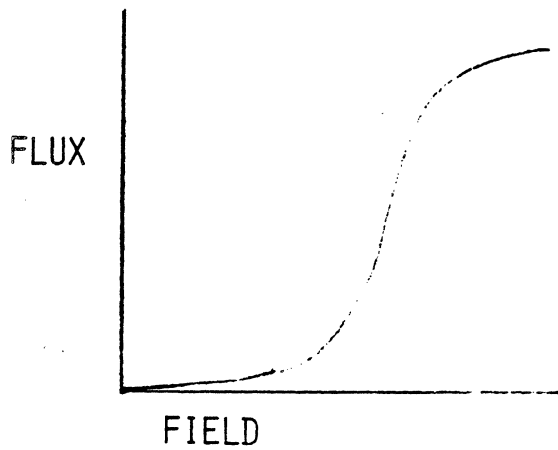




HARMONIC DISTORTION



AC BIAS RECORDING



UNBIASED RECORDING

NONLINEARITY AS A POWER SERIES

NO EVEN HARMONICS

UNCORRECTABLE BY LINEAR EQUALIZATION

EXTENSION TO INTERMODULATION

NO MEMORY EFFECTS

SUPERPOSITION APPLICABLE

NONLINEAR INTERSYMBOL INTERFERENCE

A HIGH DENSITY PHENOMENON

RELATED TO THE EXTENT OF WRITE-HEAD FIELD, AND THE TRANSITION
LENGTH, AS COMPARED TO THE BIT SPACING

DEMAGNETIZATION INTERACTION

DATA PATTERN DEPENDENT

SUPERPOSITION FAILURE

UNCORRECTABLE BY LINEAR EQUALIZATION

SHOWN IN:-

SELF-CONSISTENT FIELD CALCULATIONS

SCALE-MODELING EXPERIMENTS

→ TIME-DOMAIN MEASUREMENTS

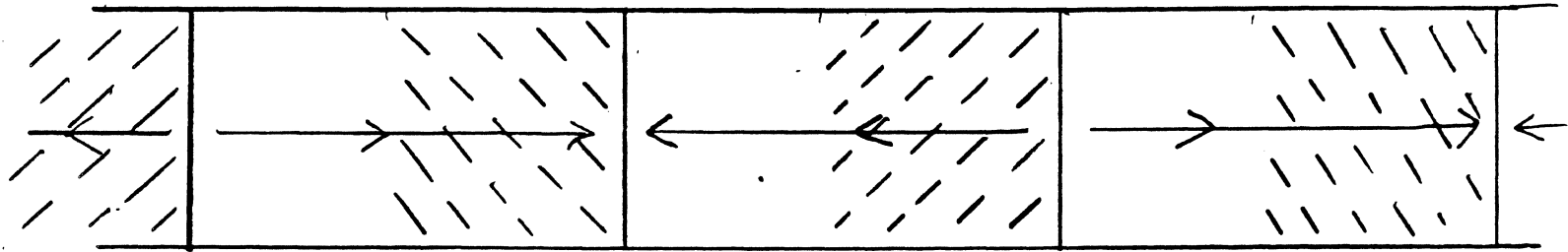
TRANSFER-FUNCTION MEASUREMENTS

C.S. Chi, "Spacing Loss and Non-linear Distortion in Digital
Magnetic Recording," IEEE Trans. Mag. V. MAG-16, Sept. 1980, pp976-78.

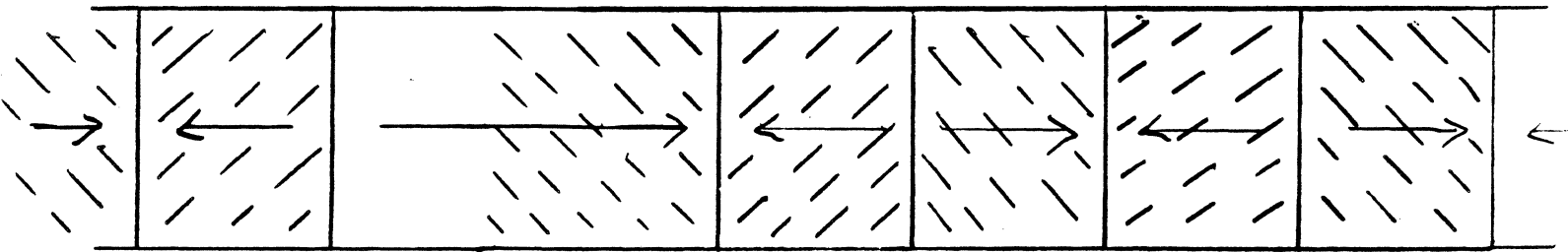
R. W. Wood & R.W. Donaldson, "The Helical-Scan Magnetic Tape
Recorder as a Digital Communication Channel," IEEE Trans. Mag.
V. MAG-15, March 1979, pp 935-43.

NONLINEAR INTERSYMBOL INTERFERENCE

"SNOWSHOE" EFFECT



LOW RECORDING DENSITY



HIGH RECORDING DENSITY

SHADED AREA = TRANSITION REGION

NOISE SOURCES IN DIGITAL RECORDING

HEAD NOISE

AMPLIFIER NOISE

MEDIA NOISE

PARTICULATE, DOMAIN, DEFECTS

MODULATION NOISE

STRAY COUPLING

FEEDTHROUGH

MULTI-TRACK HEADS

HEAD FRINGE-FIELDS

SIDE WRITING

SIDE READING

CORNER READING

OVERWRITE NOISE

TRACK MISREGISTRATION

OFF-TRACK

ADJACENT TRACK

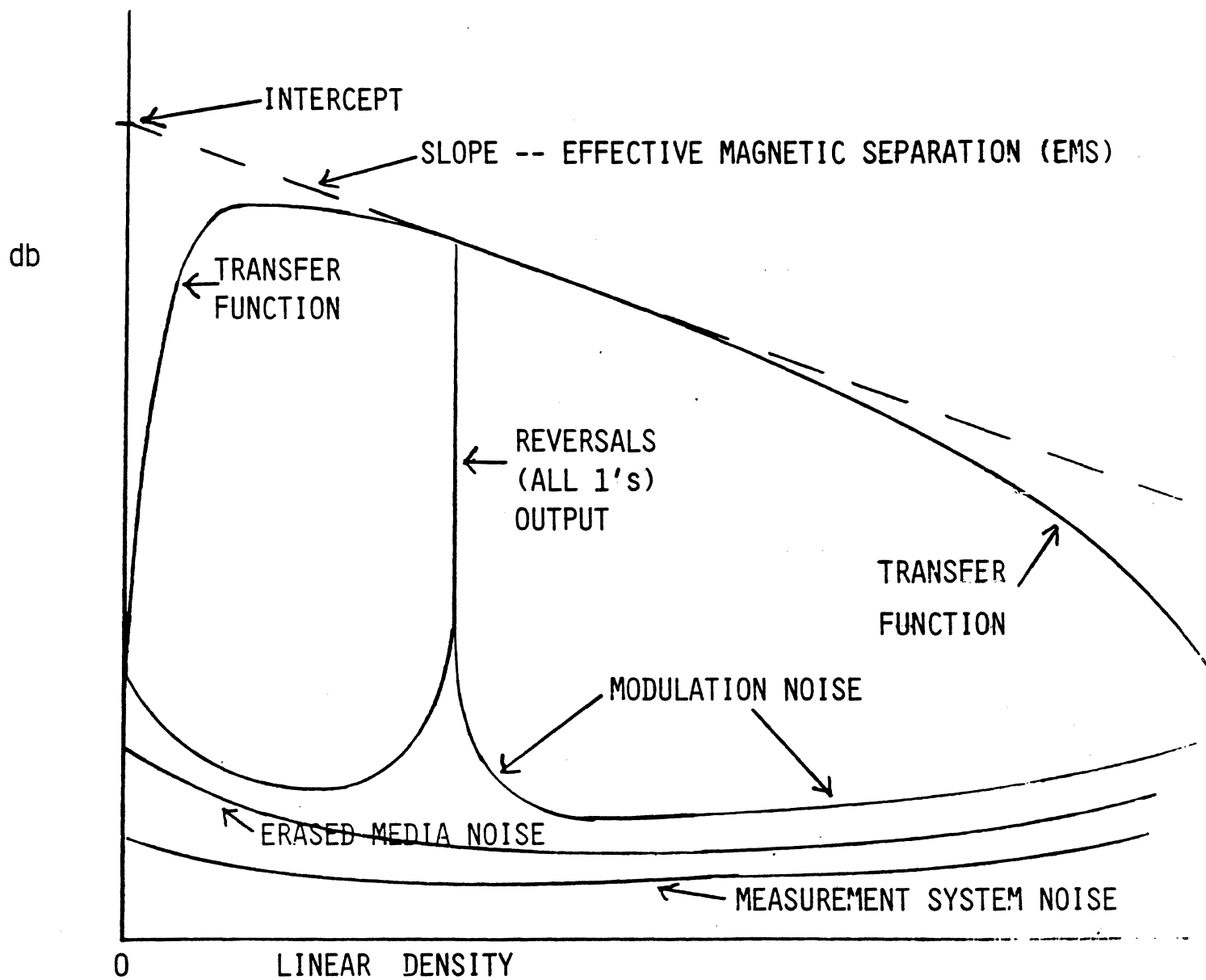
OLD INFORMATION

MECHANICAL VIBRATIONS AND VARIATIONS

VELOCITY

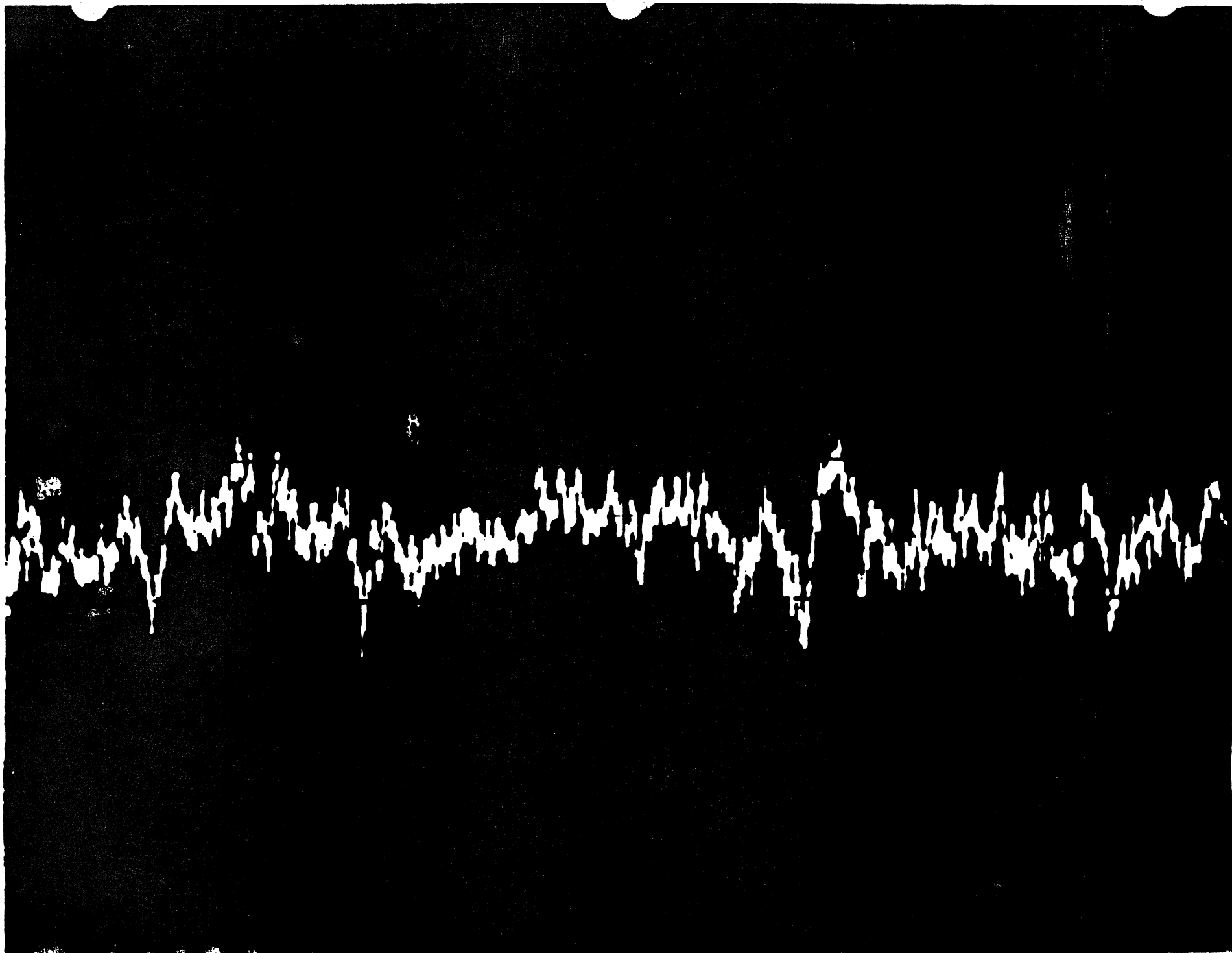
TRACKING

DENSITY RESPONSE AND NOISE





Pos Twp.



Digital Computation of Noise Spectrum

Given a Time Series: x_t , $t = 0, 1, 2 \dots N$

$$\text{Mean: } \bar{x} = \frac{1}{N} \sum_{t=1}^N x_t$$

$$\text{Variance: } \sigma_x^2 = \frac{1}{N} \sum_{t=1}^N (x_t - \bar{x})^2$$

$$\begin{aligned} \text{Auto-Covariance: } c_{xx}(k) &= \frac{1}{N} \sum_{t=1}^{N-k} (x_t - \bar{x})(x_{t+k} - \bar{x}) \\ k &= 0, 1, 2, \dots, (N-1) \\ k &= \text{lag} \end{aligned}$$

$$c_{xx}(0) = \sigma_x^2$$

$$\text{Autocorrelation Function: } r_{xx}(k) = \frac{c_{xx}(k)}{c_{xx}(0)}$$

Spectral Density Function:

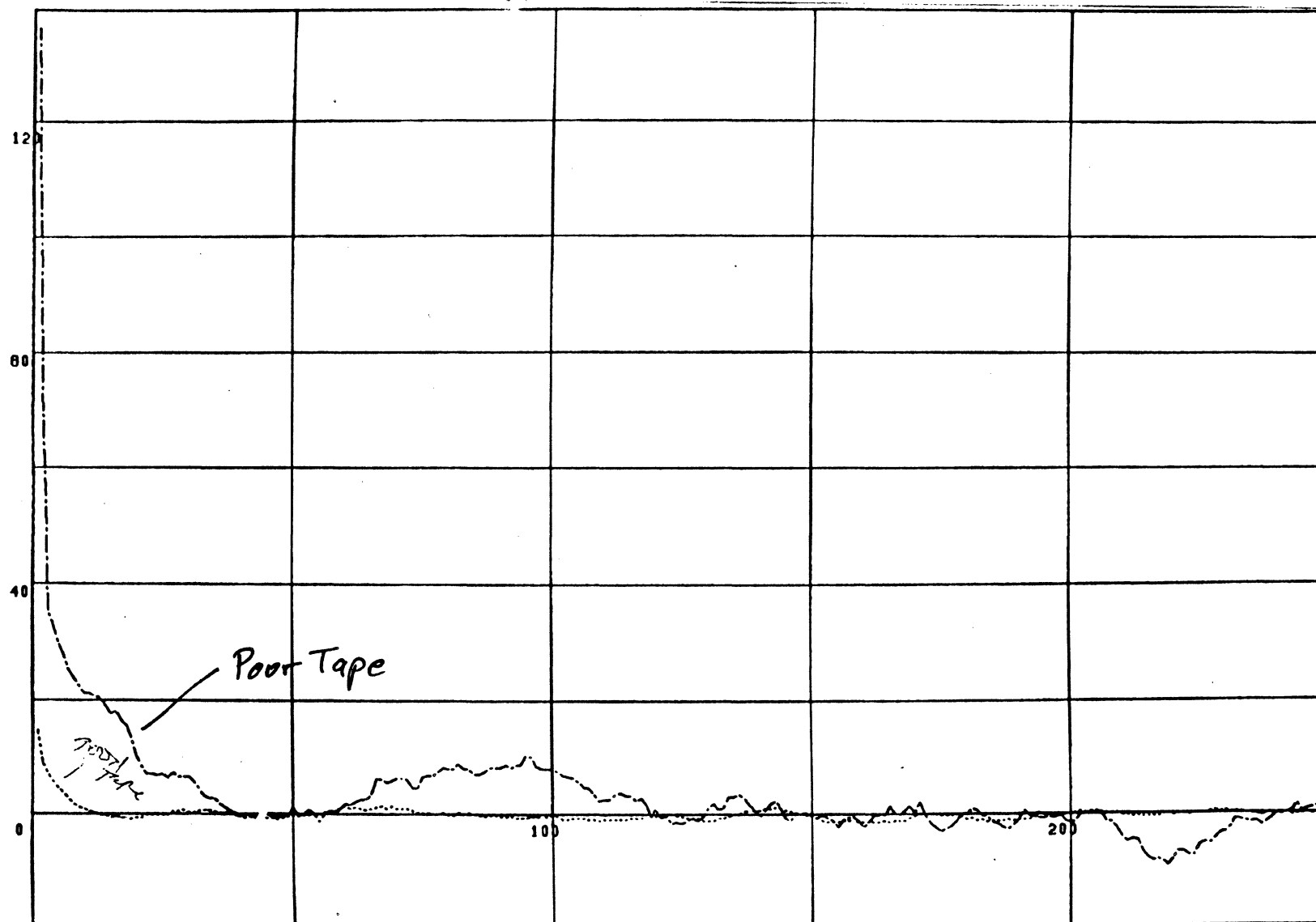
$$\bar{R}_{xx}(f) = \text{Fourier Transform of Autocorrelation Function}$$

Power Spectrum:

$$\bar{C}_{xx}(f) = \sigma_x^2 \times \text{Spectral Density Function}$$

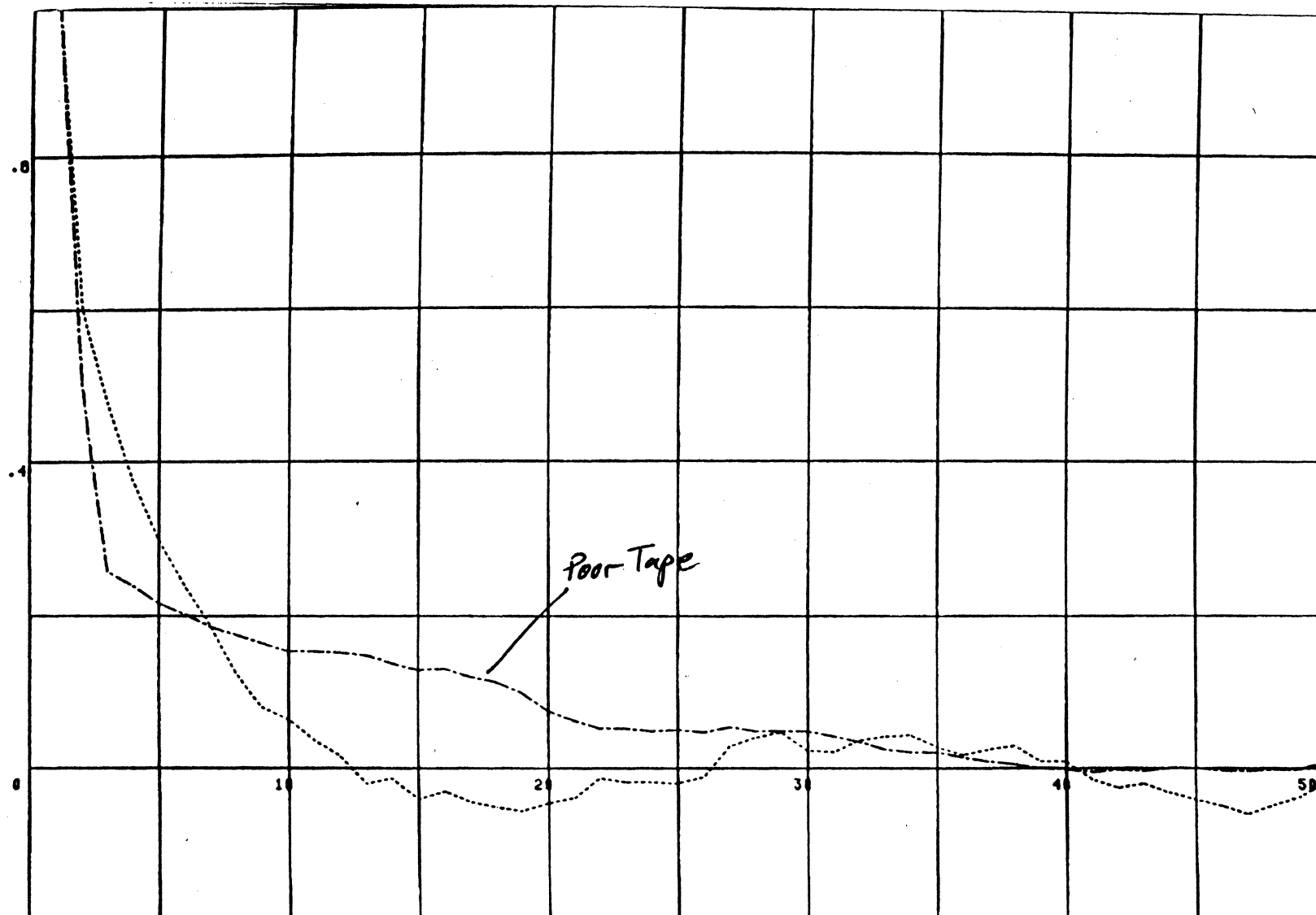
Jenkins & Watts, Spectral Analysis and its Applications,
San Francisco: Holden Day, 1968

AUTO-COVARIANCE



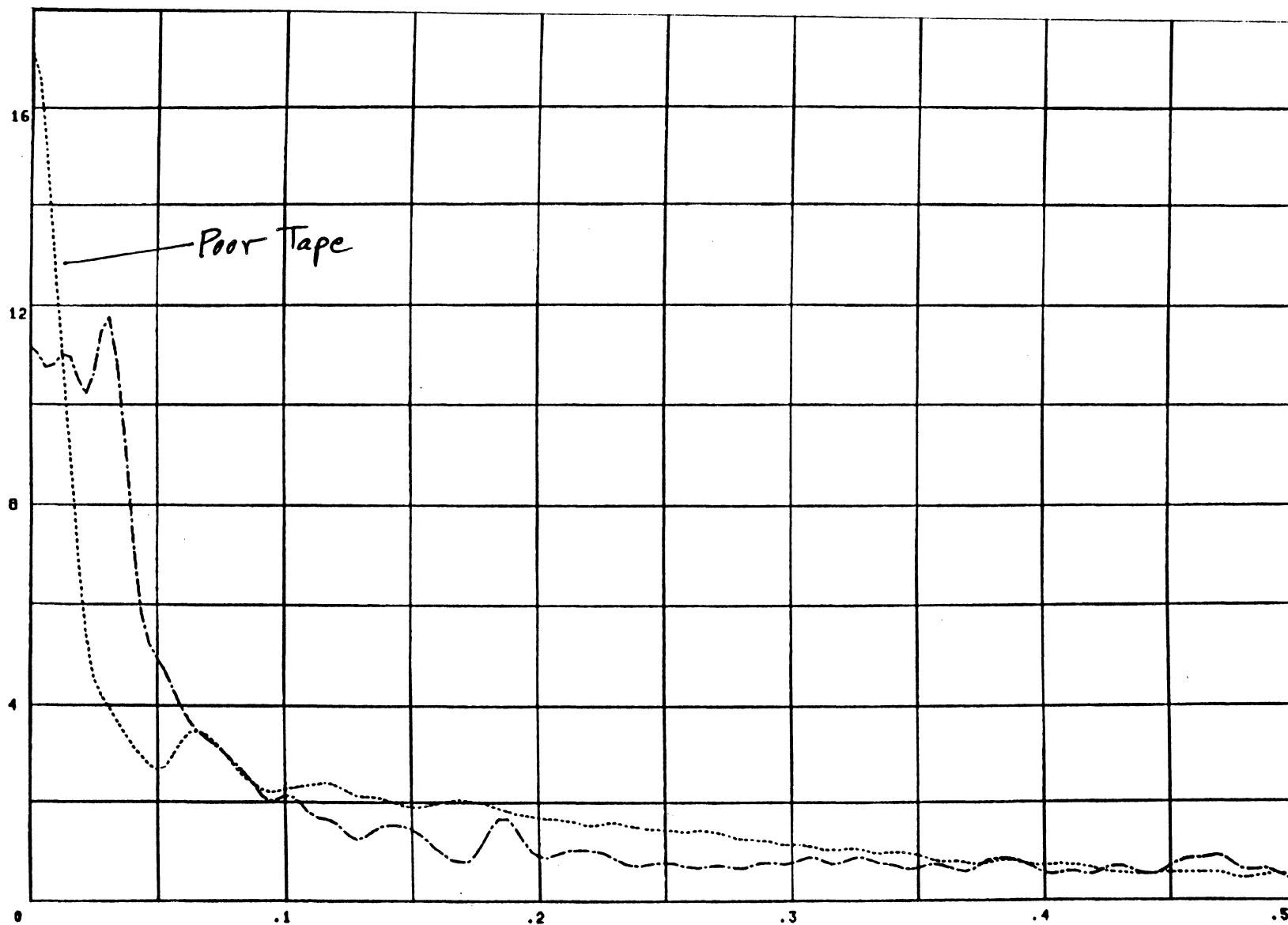
Lag →

AUTO-CORRELATION FUNCTION



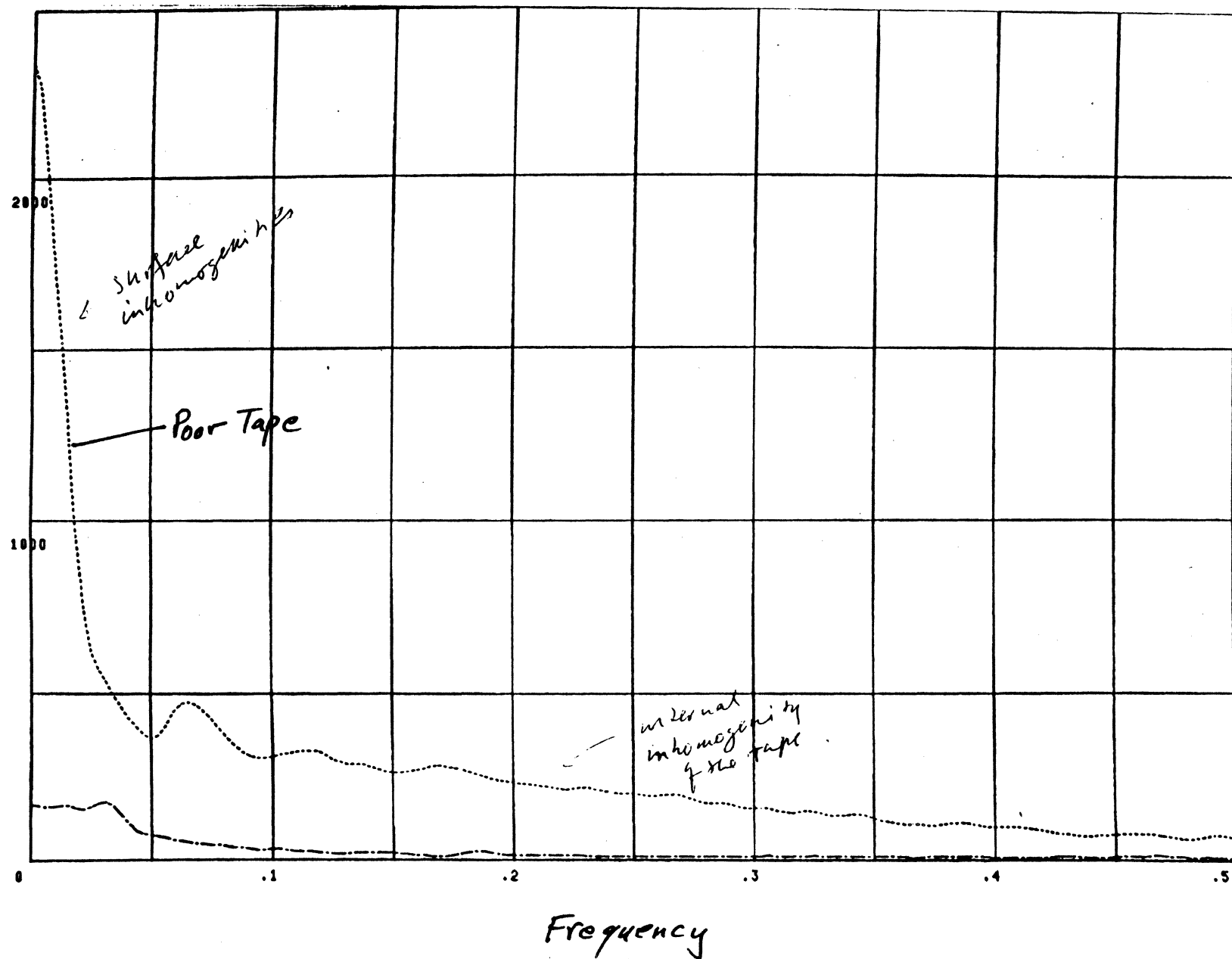
Lag →

SPECTRAL DISTRIBUTION



Frequency → (spatial) 5000 cycles/in

NOISE SPECTRUM

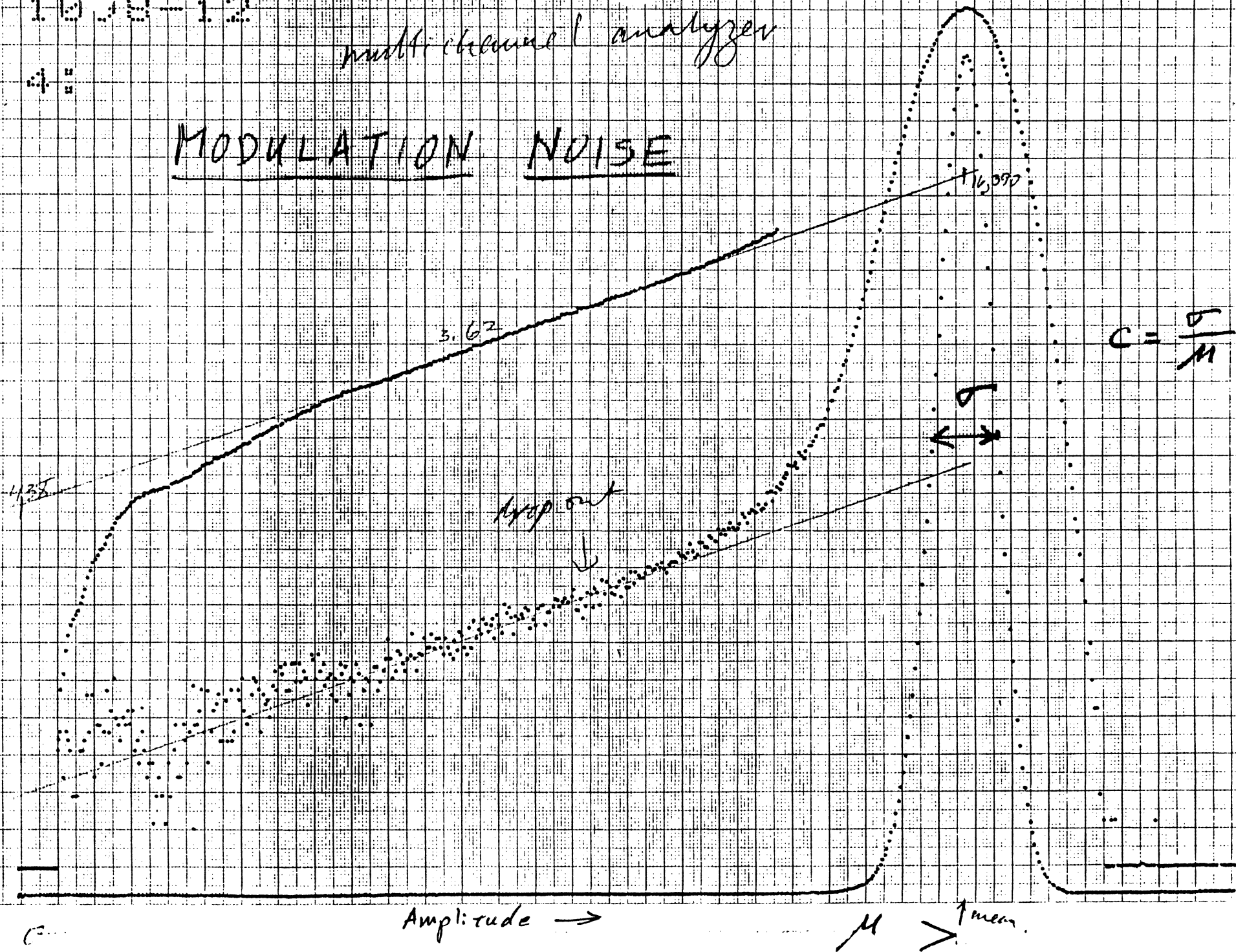


10-8-12

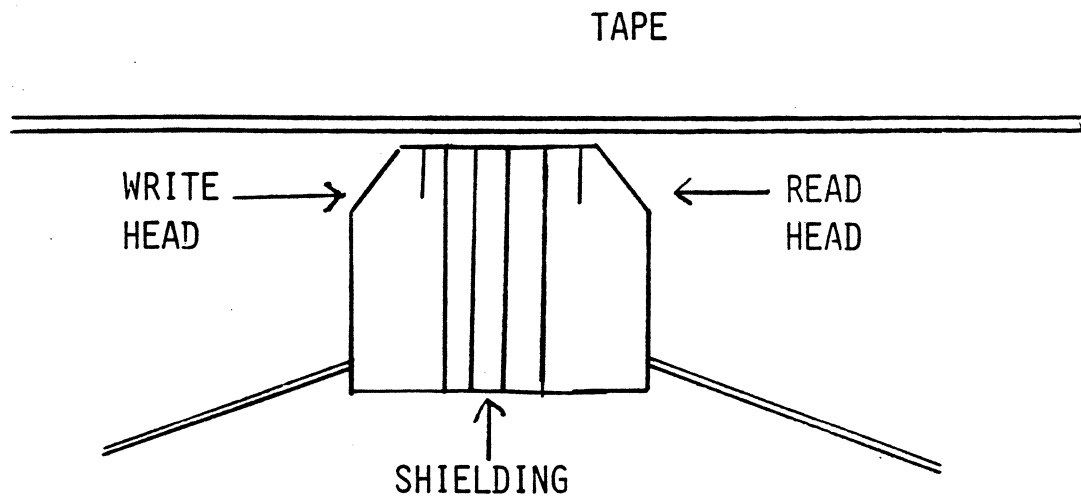
4

multi-channel analyzer

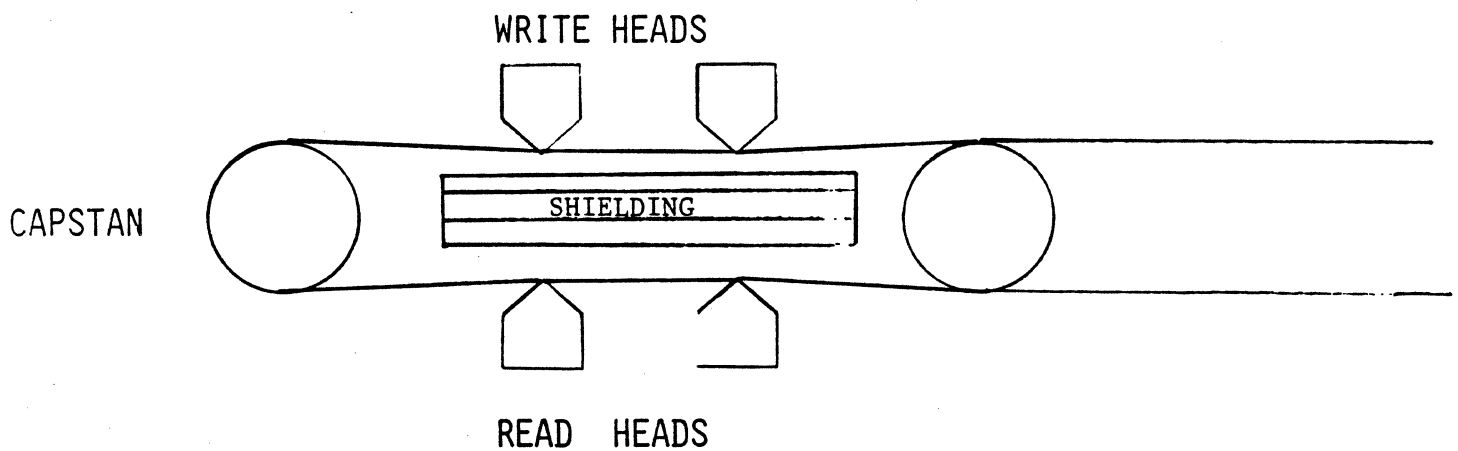
MODULATION NOISE



FEEDTHROUGH NOISE



COMBINED READ-WRITE HEAD



SEPARATE READ AND WRITE HEADS

COUPLING FROM WRITE HEAD AND CABLES TO READ HEAD
READ-WHILE-WRITE OPERATION ONLY

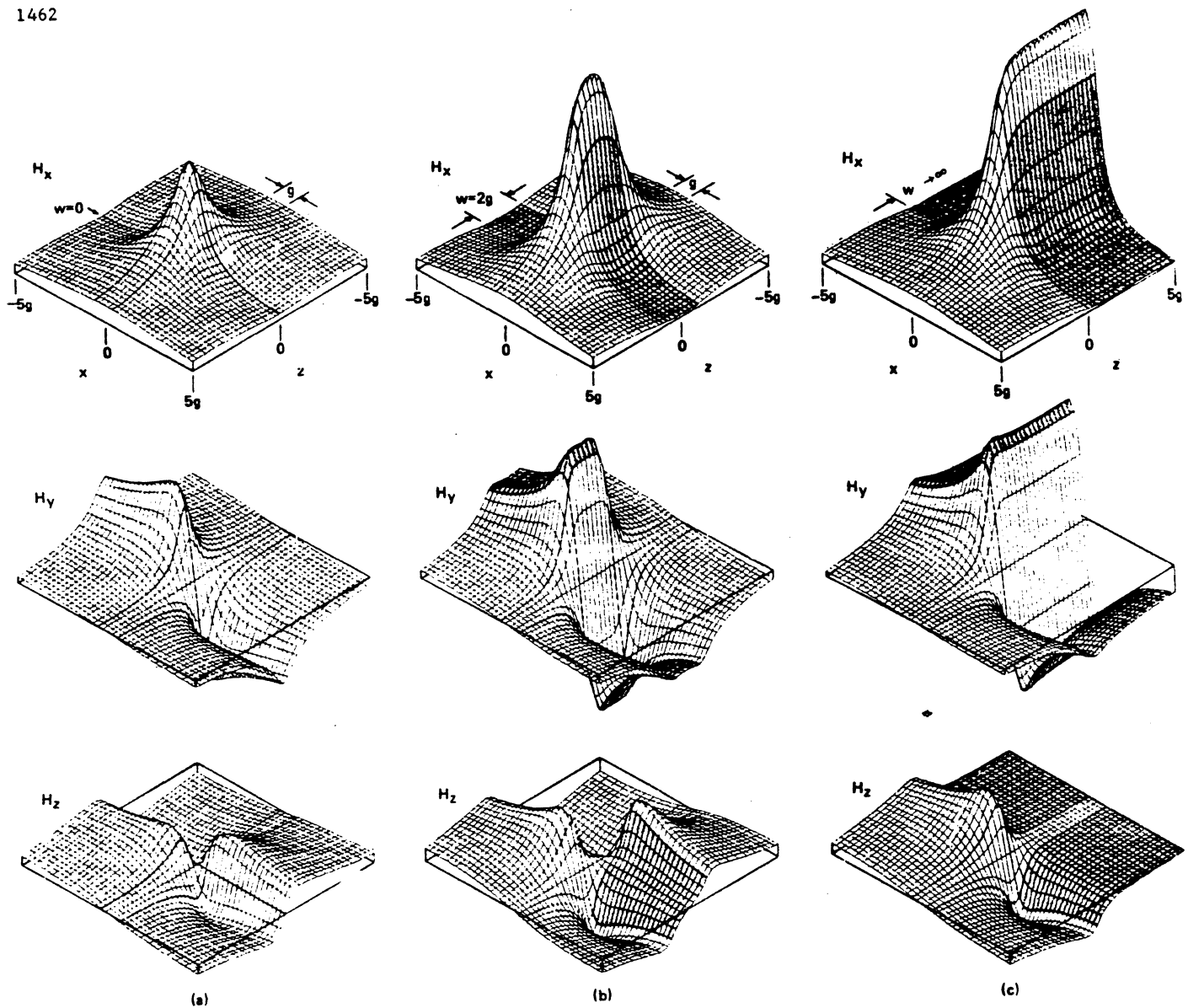


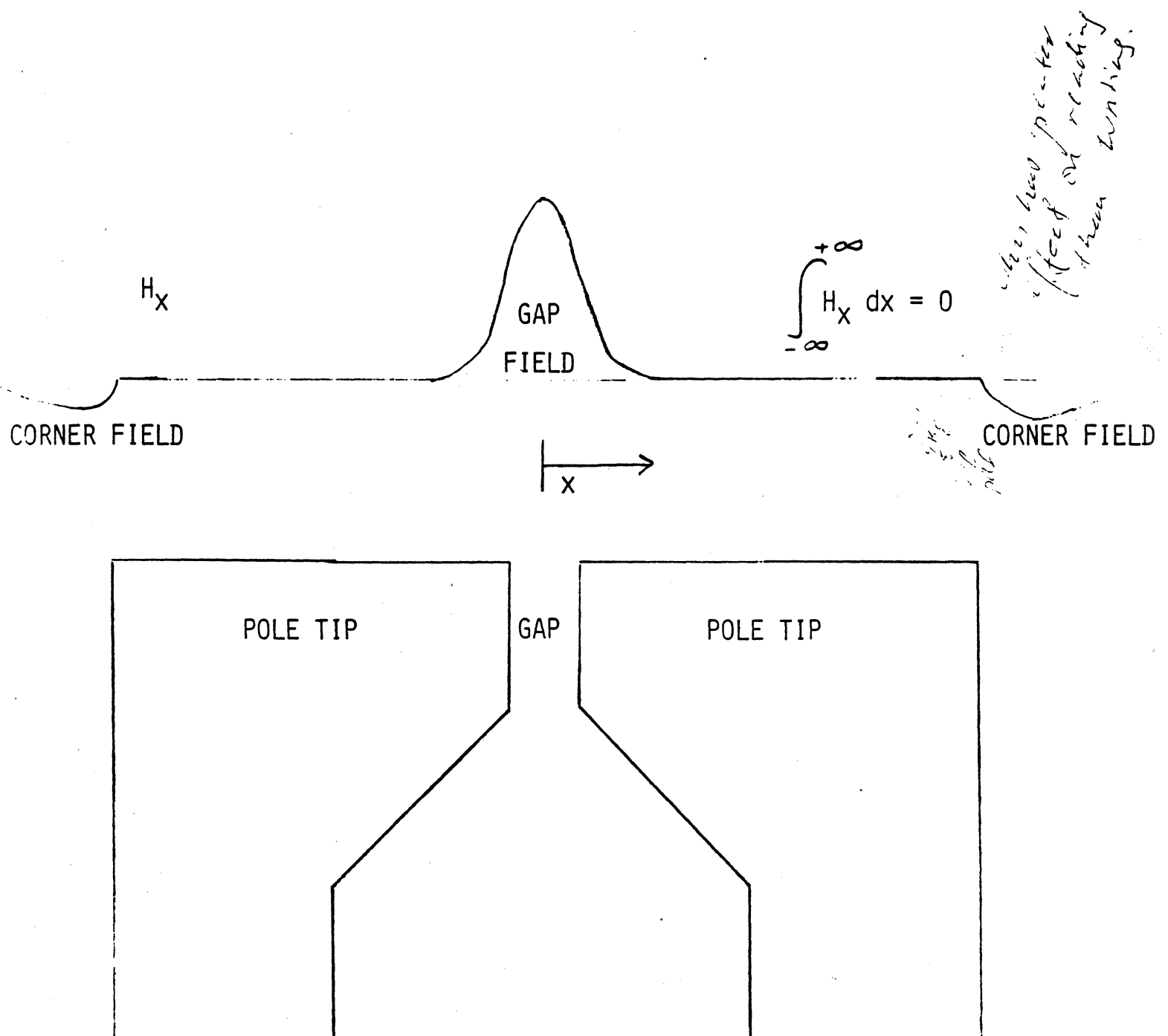
Figure 4. Magnetic fields at $y=g/2$ for (a) zero width head, (b) finite width head, $w=2g$, and (c) semi-infinite width head. Components are: longitudinal (H_x), vertical (H_y), and transverse (H_z). Projected onto each field surface are the outlines of the top of the head with edge extensions.

HEAD FIELD DISTRIBUTIONS

D. A. Lindholm, "Magnetic Fields of Finite Track Width Heads,"
IEEE Trans. Mag. Vol. MAG-13, Sept. 1977

READ-SEPARATION DEPENDENT
DENSITY DEPENDENT

HEAD-CORNER READING EFFECT



OVERWRITE-ERASURE NOISE

ERASE PROBLEM

DC ERASE, AC ERASE

DENSITY DEPENDENCE

TRANSITION REGION

FINITE DEPTH RECORDING

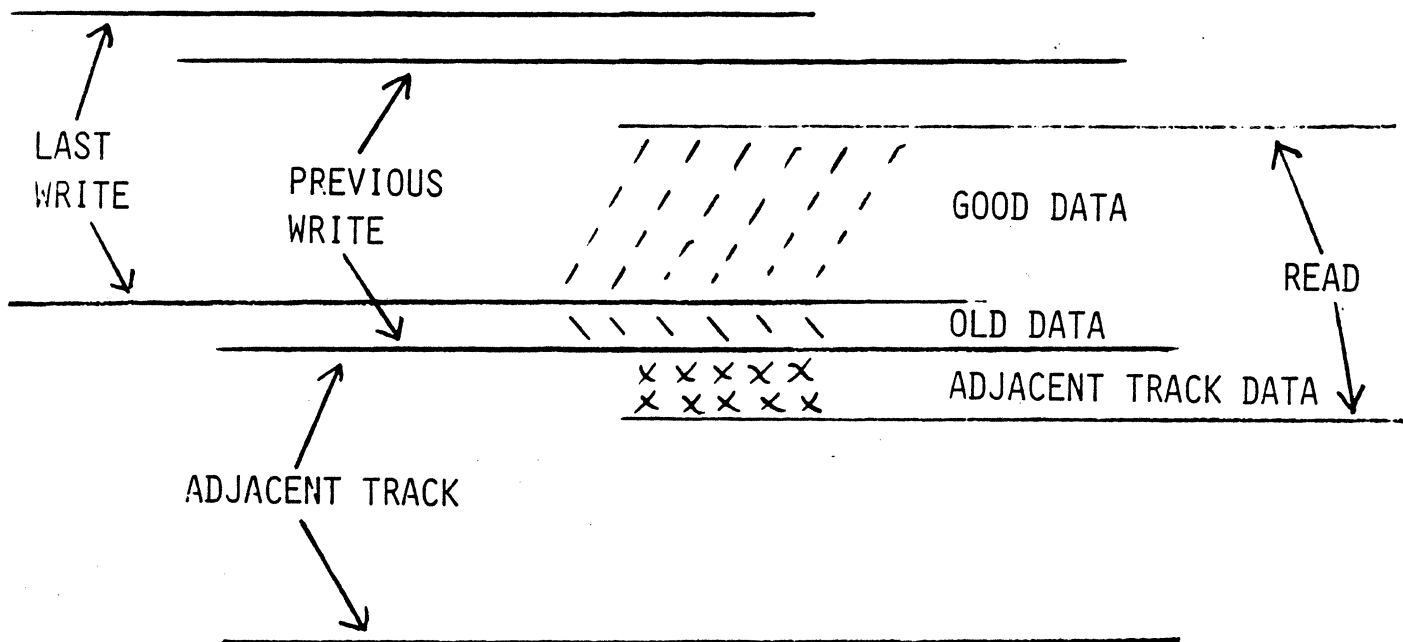
FLYING-HEIGHT VARIATION

UNBIASED, AC BIAS, RECORDING

CODED WRITE-DATA SPECTRUM

difficult to erase low density vs high density

TRACK MISREGISTRATION (TMR)



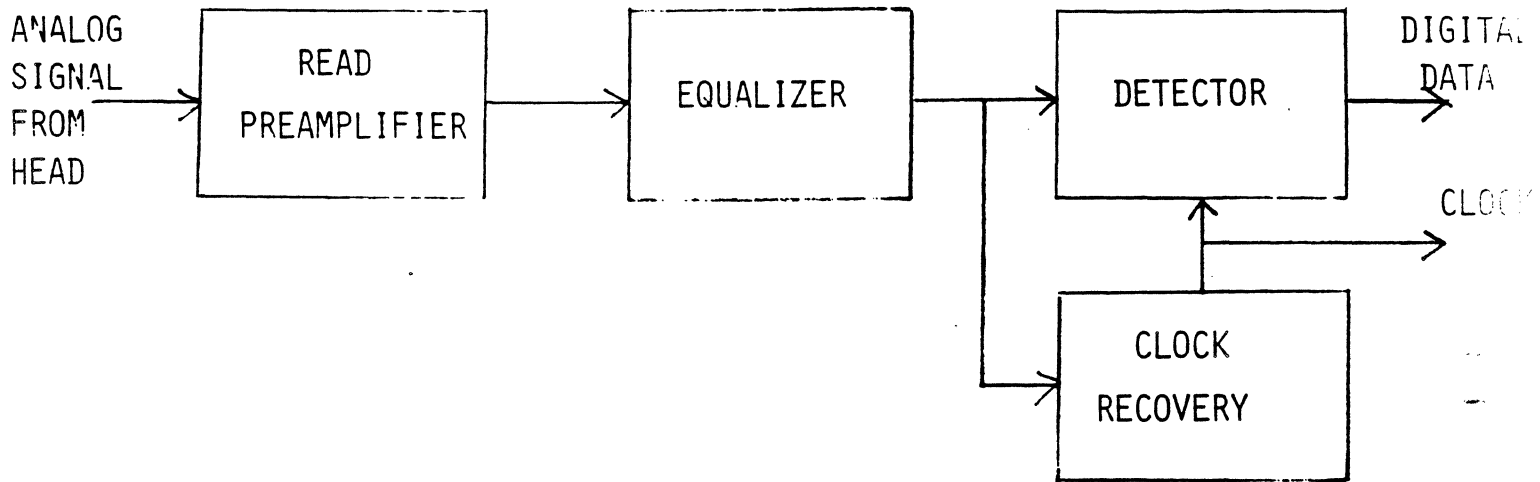
GUARD BAND

TUNNEL ERASE

WRITE WIDE, READ NARROW

SERVO TRACK FOLLOWING

READ-ELECTRONICS CHAIN

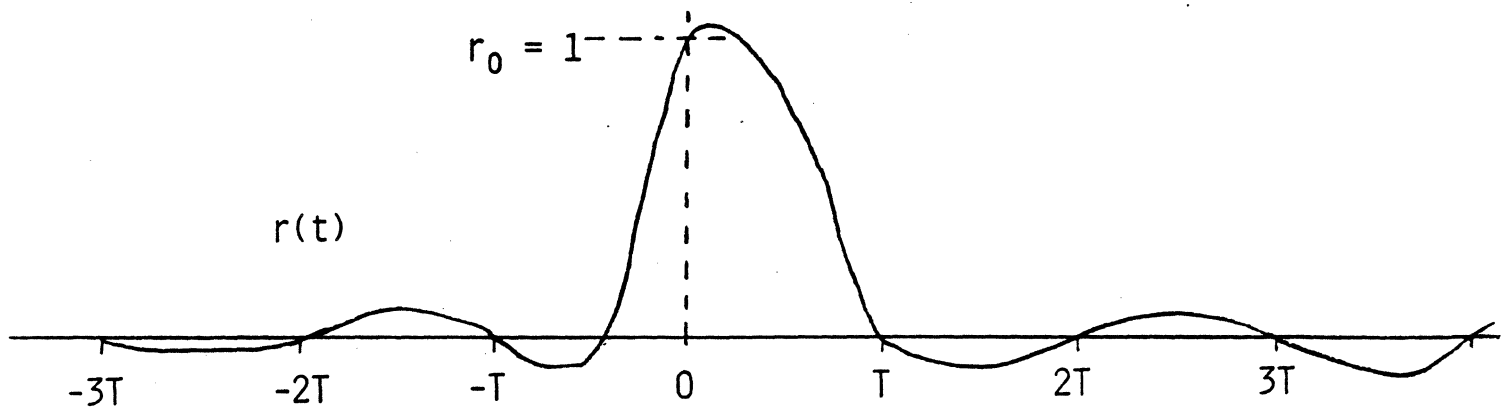


BENNETT & DAVY, DATA TRANSMISSION, NEW YORK: MCGRAW-HILL, 1965.

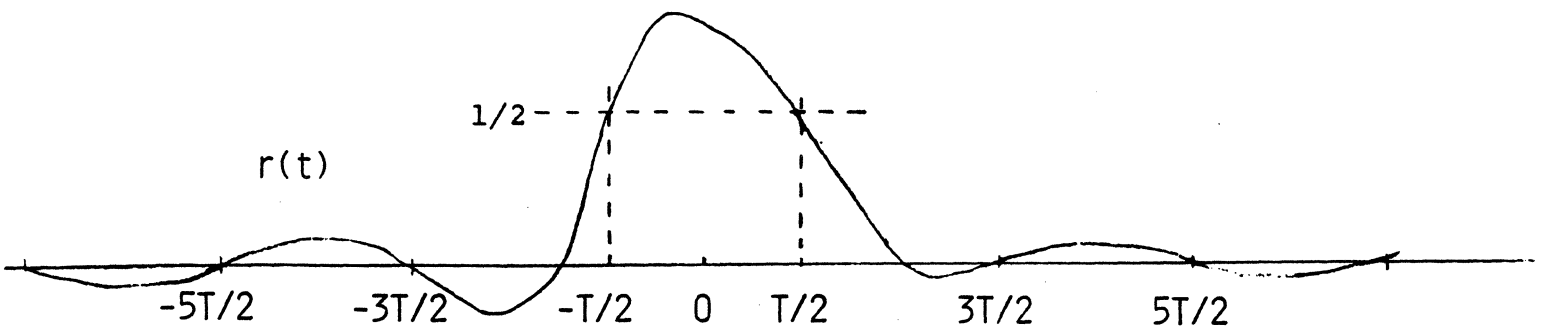
EQUALIZATION:-

GIBBY & SMITH, B.S.T.J., V44, Sept. 1965, pp 1487-1510

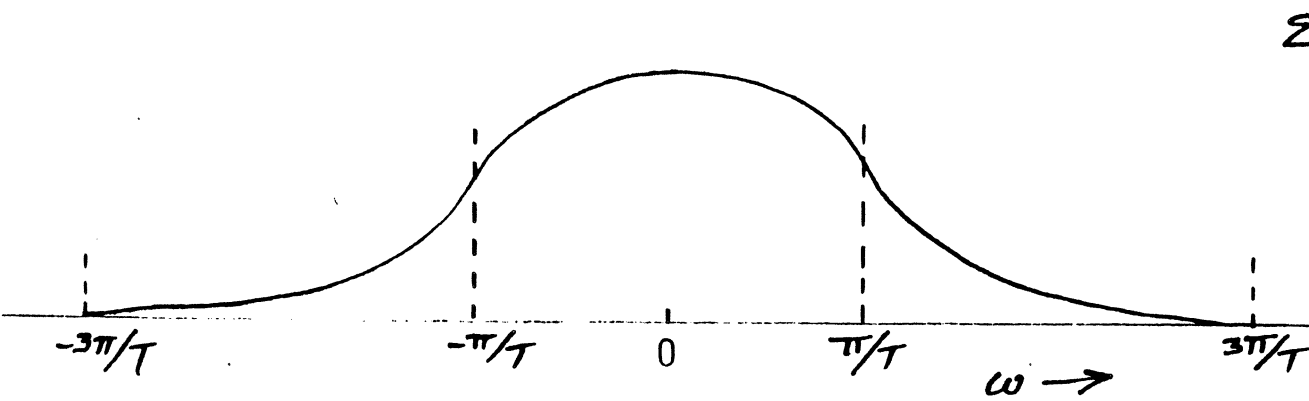
EQUALIZING SAMPLED DATA



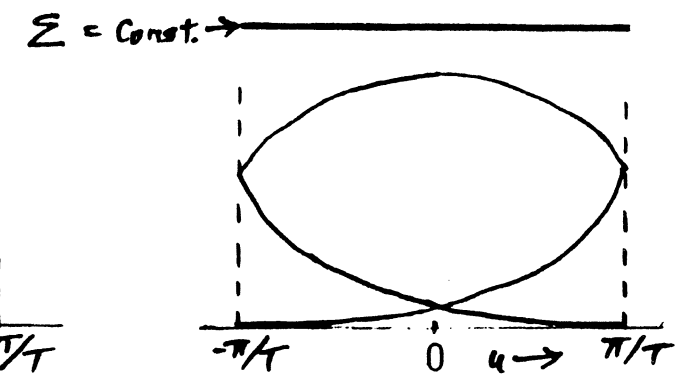
CONTROLLING AMPLITUDE AT SAMPLE POINTS



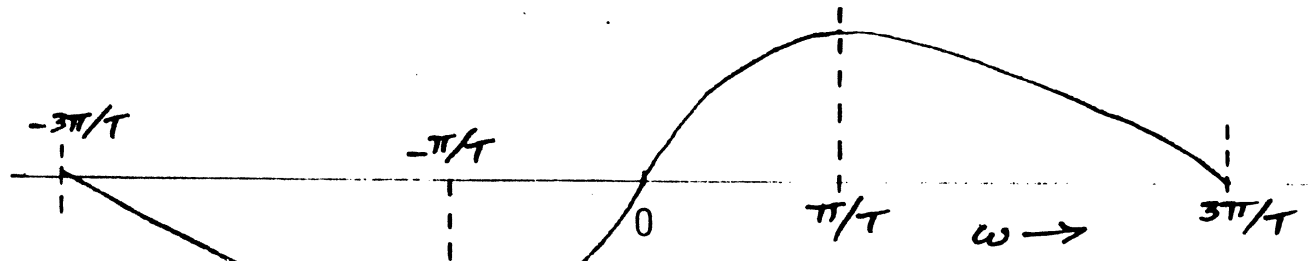
CONTROLLING PULSE WIDTH BETWEEN SAMPLE POINTS



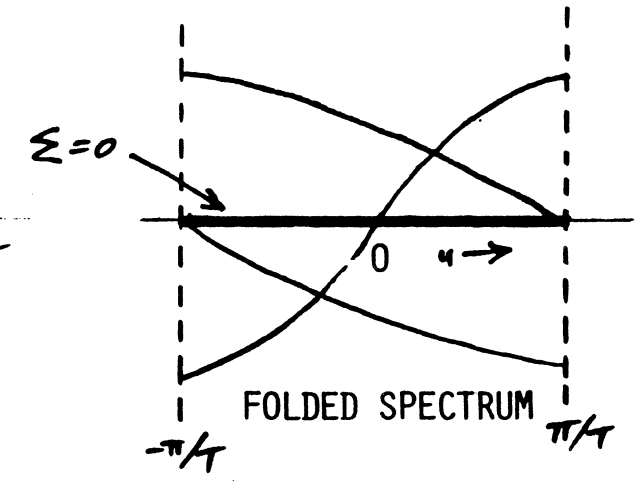
REAL COMPONENT OF SIGNAL SPECTRUM



FOLDED SPECTRUM

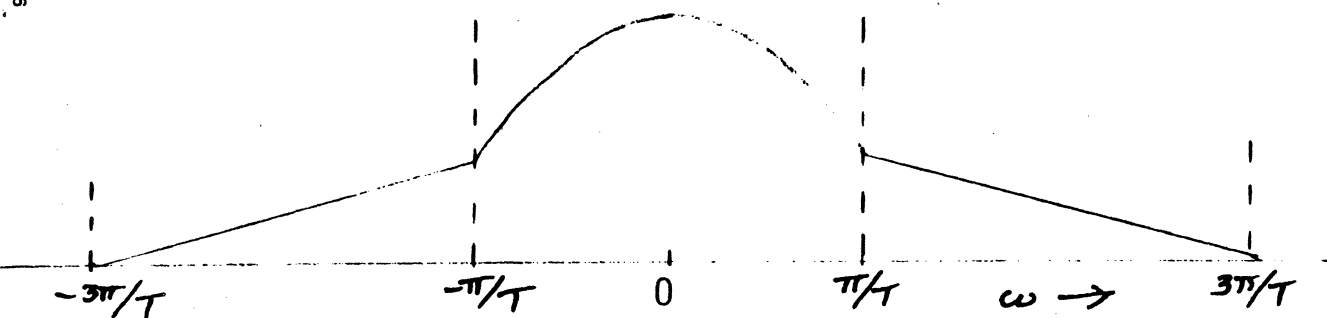


IMAGINARY COMPONENT OF SIGNAL SPECTRUM

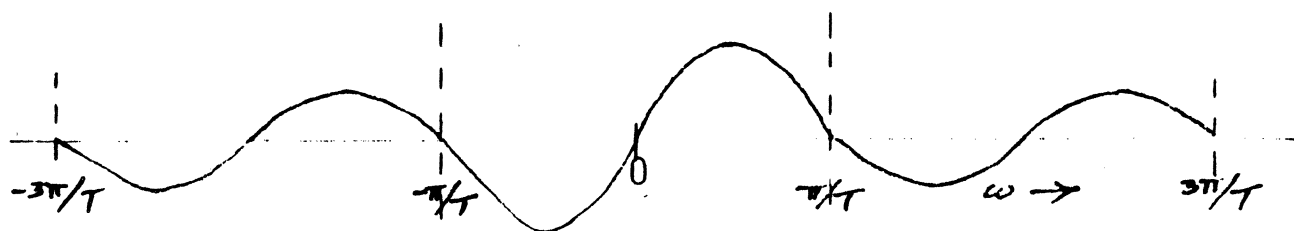
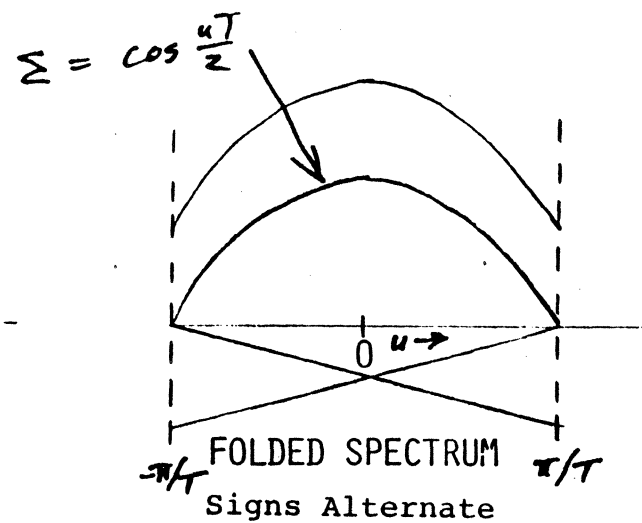


FOLDED SPECTRUM

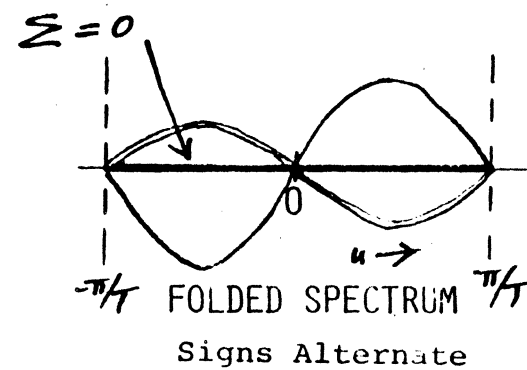
EXAMPLE:-- SPECTRUM THAT CONTROLS AMPLITUDE AT SAMPLE POINTS



REAL COMPONENT OF SIGNAL SPECTRUM

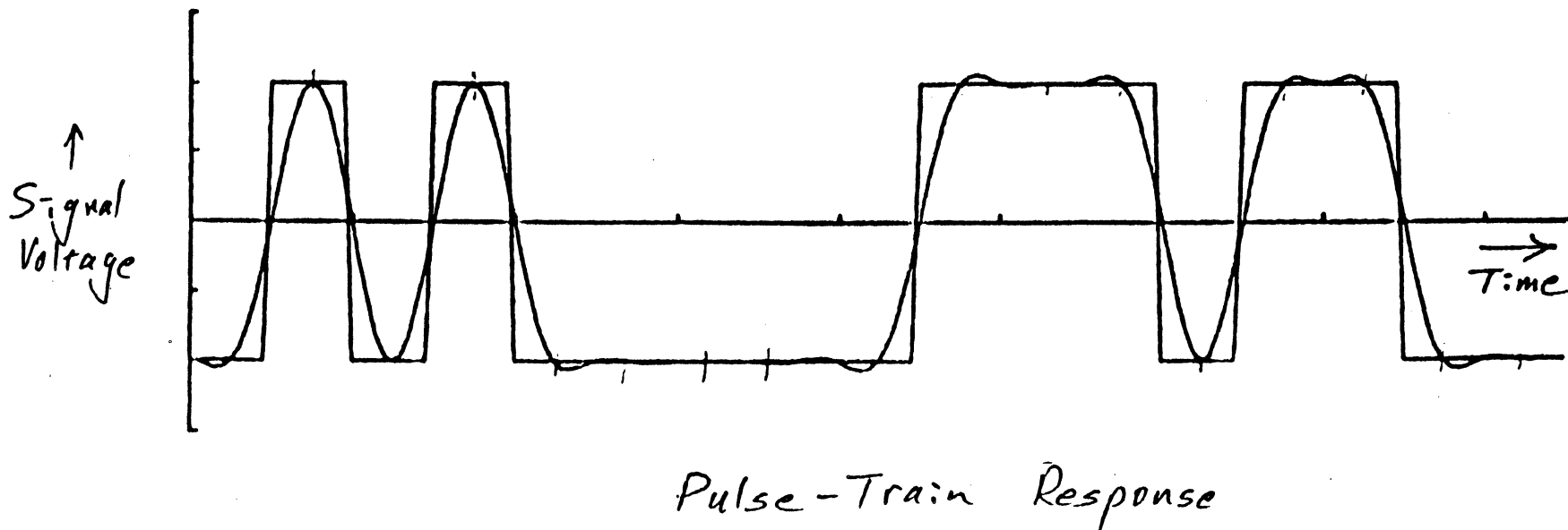
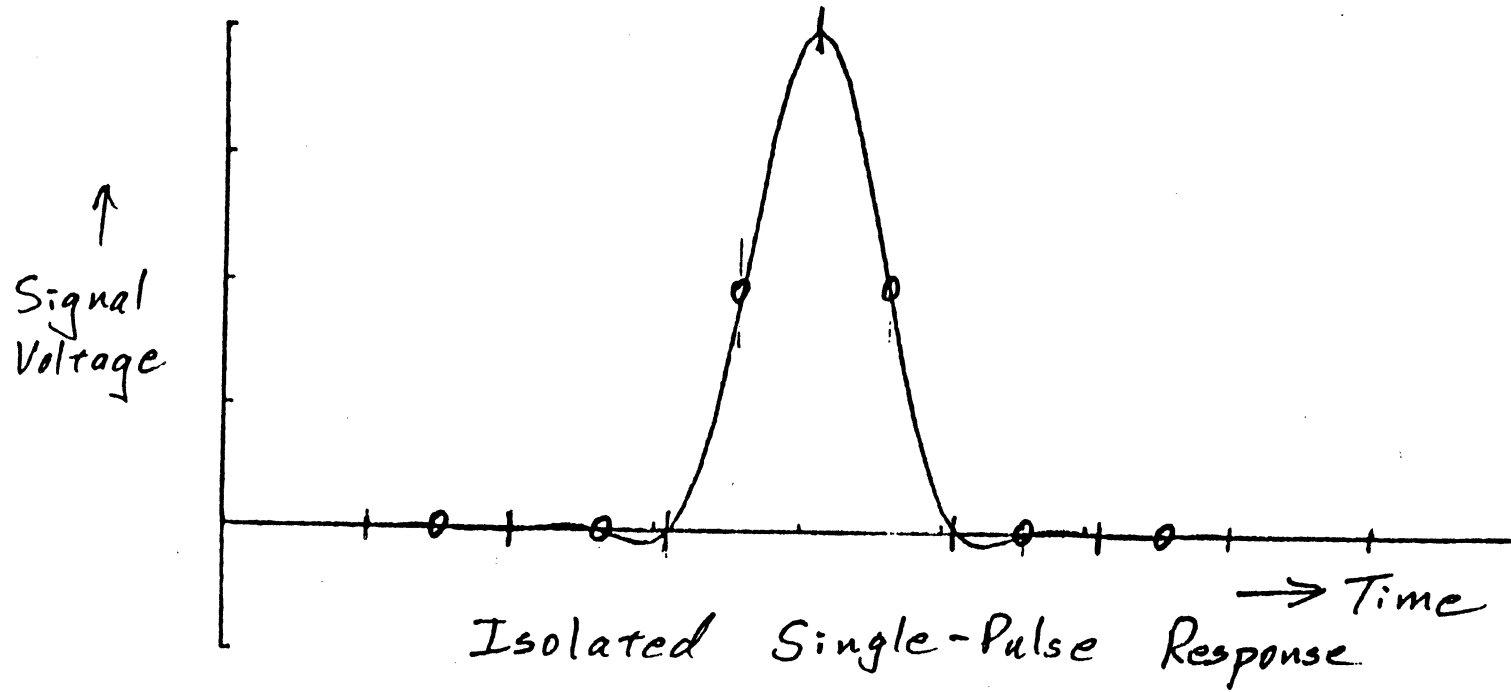


IMAGINARY COMPONENT OF SIGNAL SPECTRUM

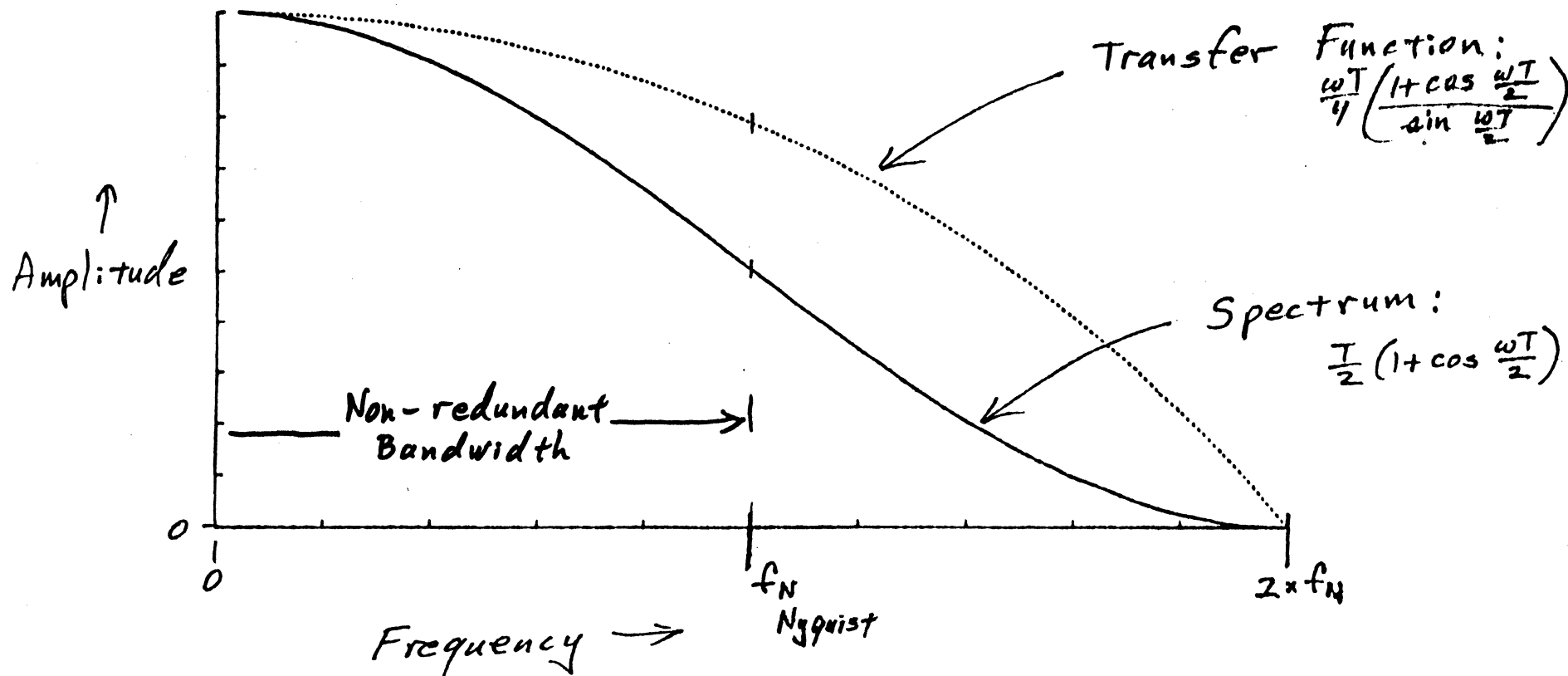


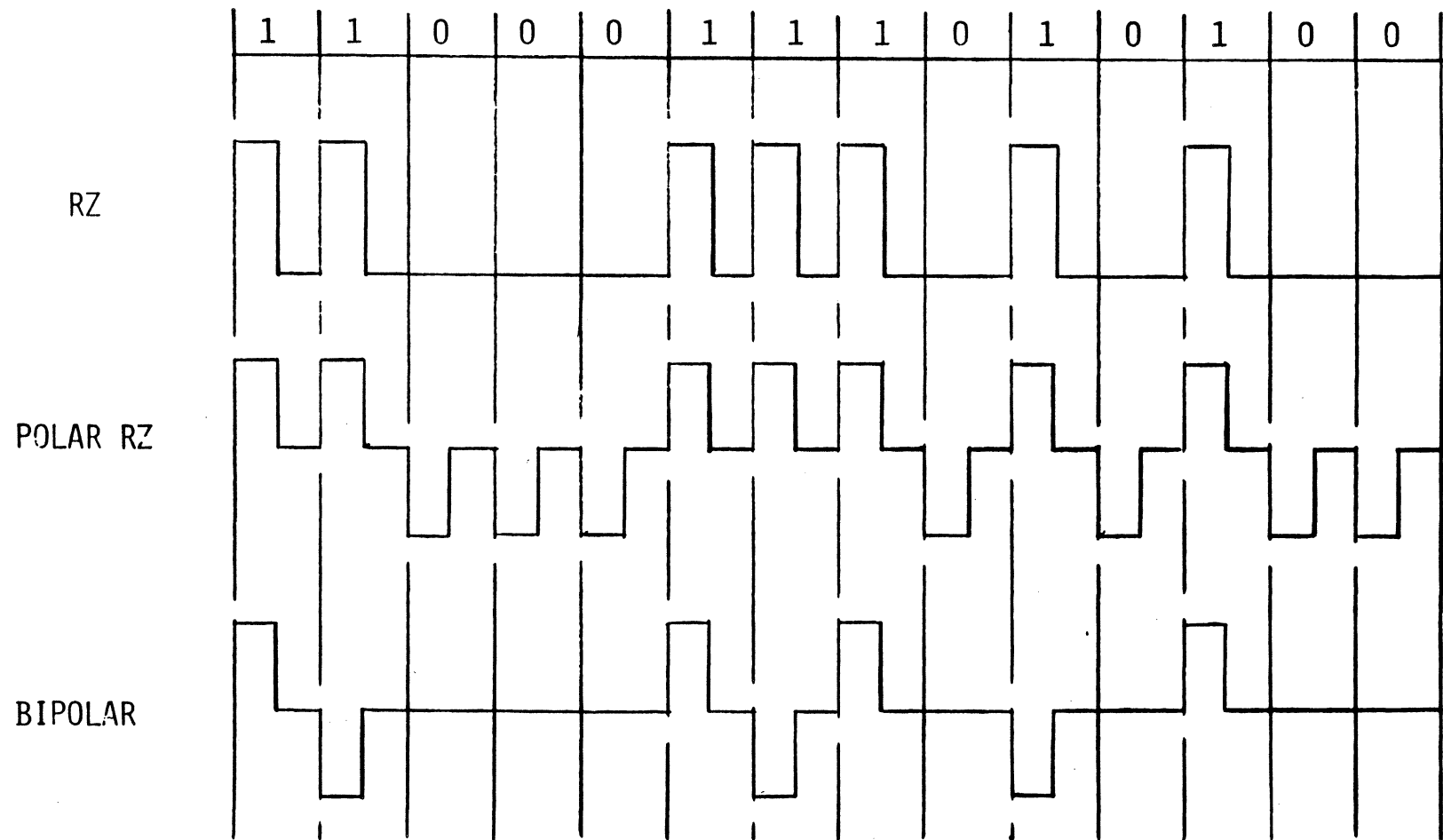
EXAMPLE:-- SPECTRUM THAT CONTROLS PULSE-WIDTH AT SAMPLE POINTS

"RAISED - COSINE" CHANNEL

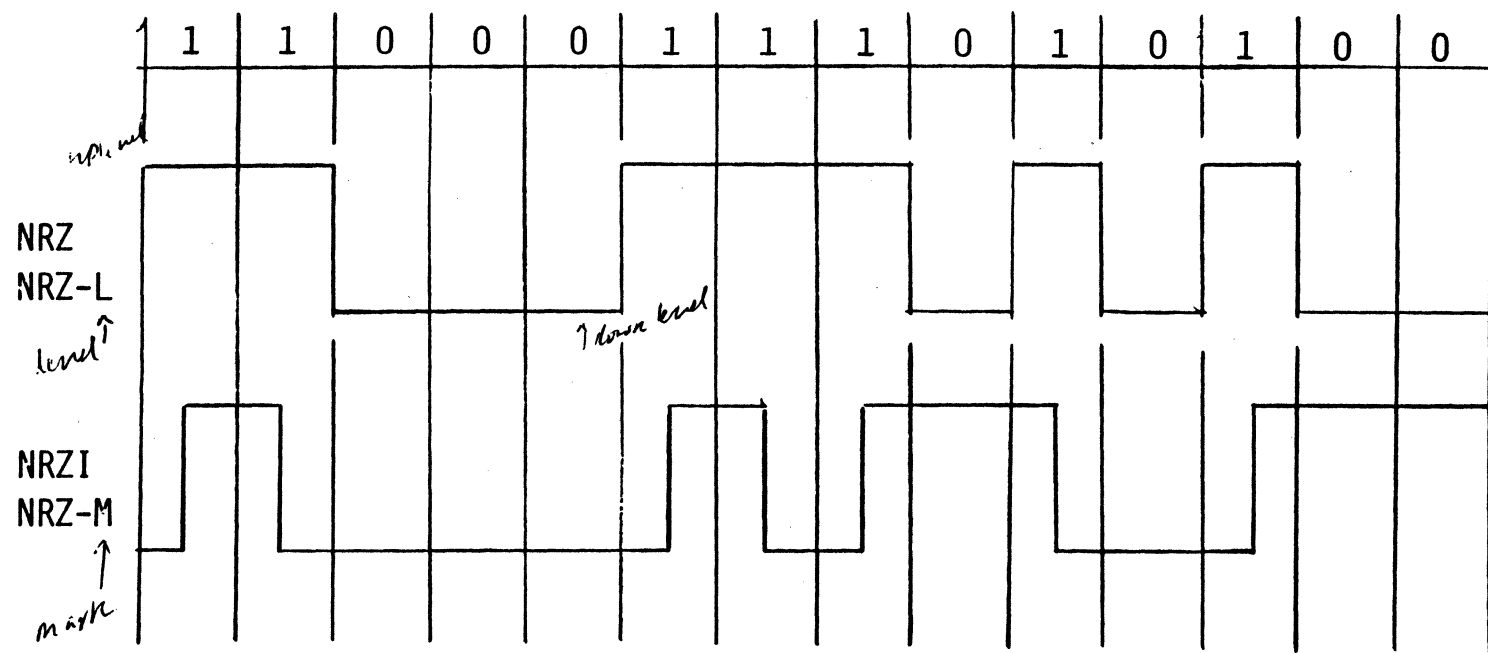


"RAISED - COSINE" CHANNEL





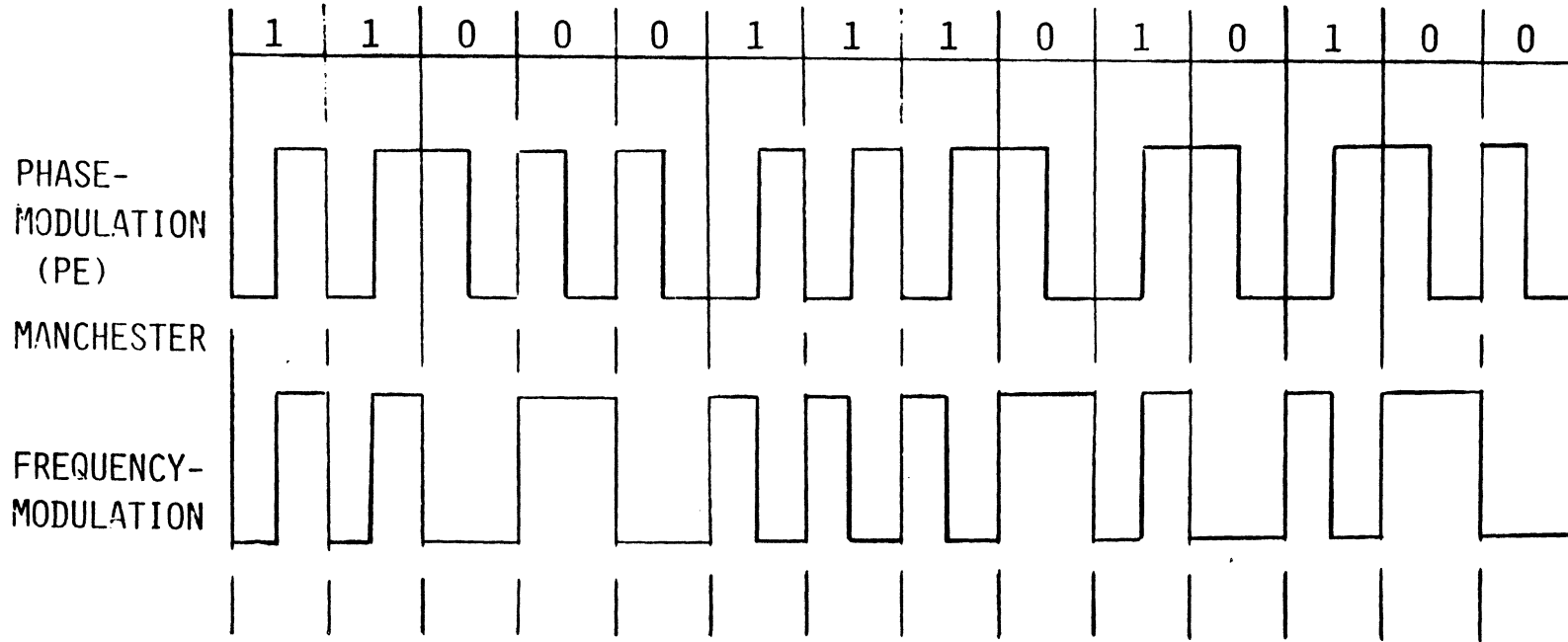
RETURN-TO-ZERO (RZ) CODES



↑
change
'incl when
you see 1'

NON-RETURN-TO-ZERO (NRZ) CODES

1 - 2 - not + up
0 - 2 - not - up



DOUBLE-FREQUENCY CODES

Same as NRZI
+ additional ~~signal~~
signal at every bit
for clocking.

Transition occurs in the window
 no 1 set cells + add. signal when we have 20

MILLER
 DELAY-MODULATION
 MFM

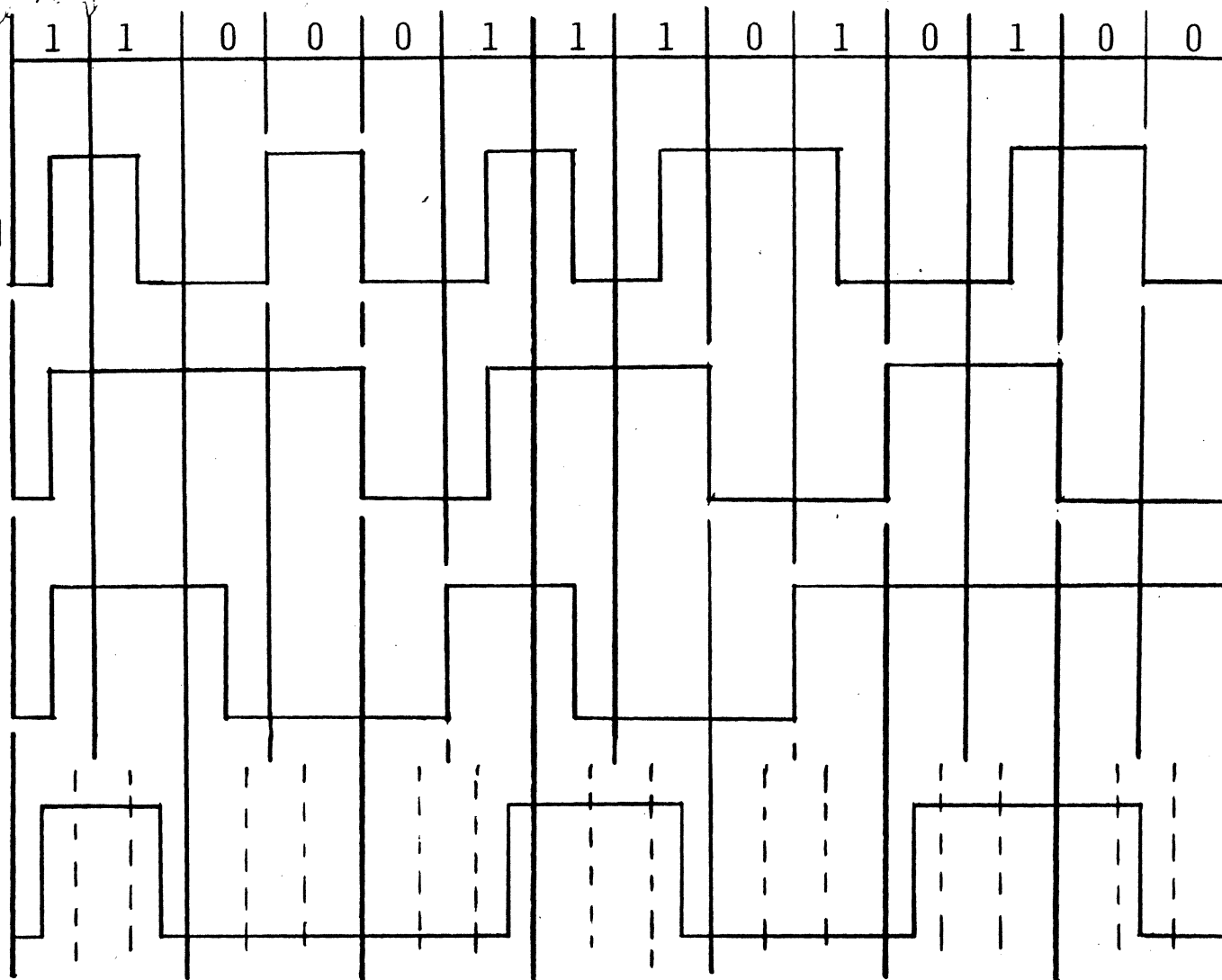
modified FM

2,7 RUN-LENGTH

min max 1/2 window

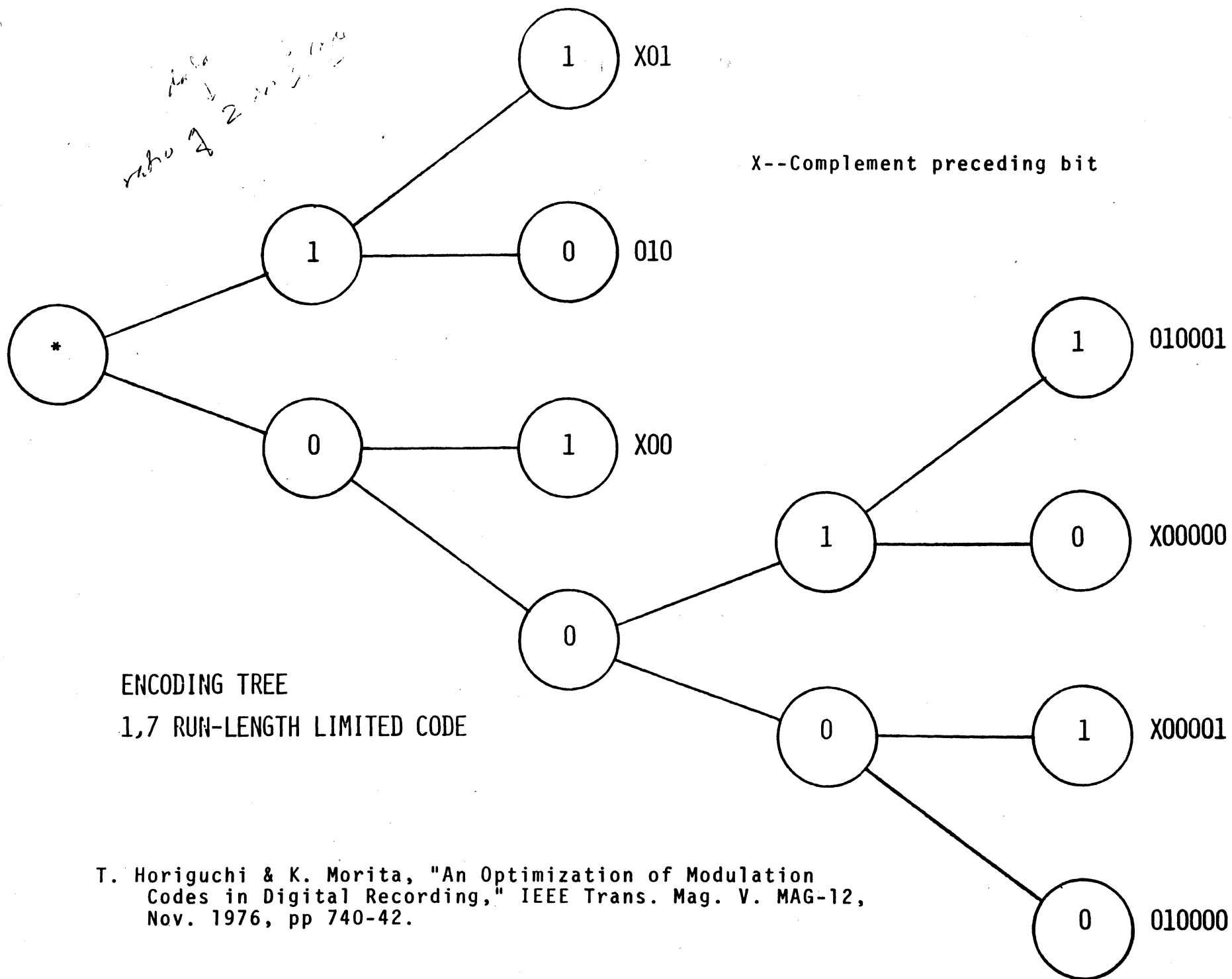
3PM

1,7 RUN-LENGTH



FRACTIONAL-WINDOW CODES

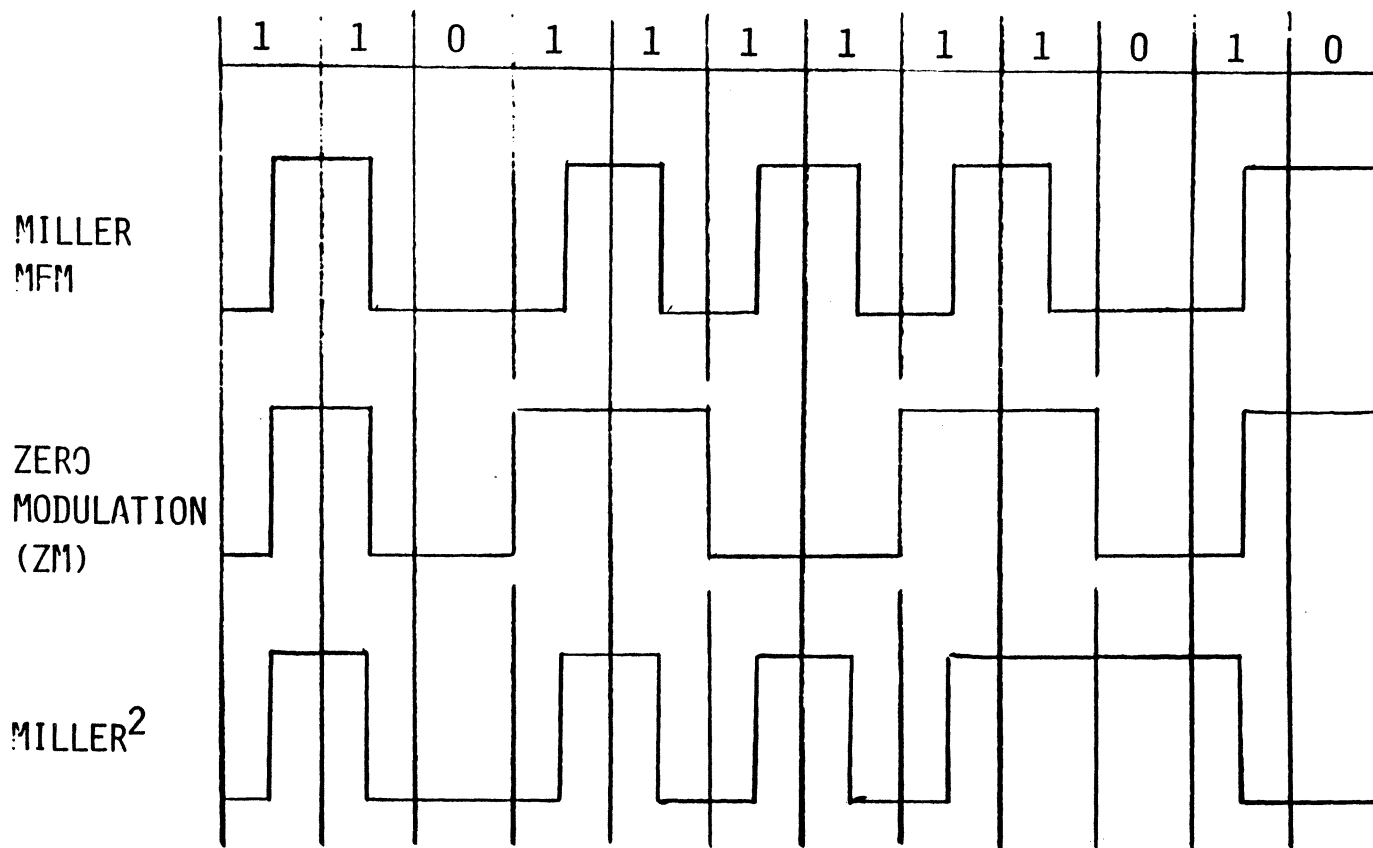
*info
ratio 2/3*



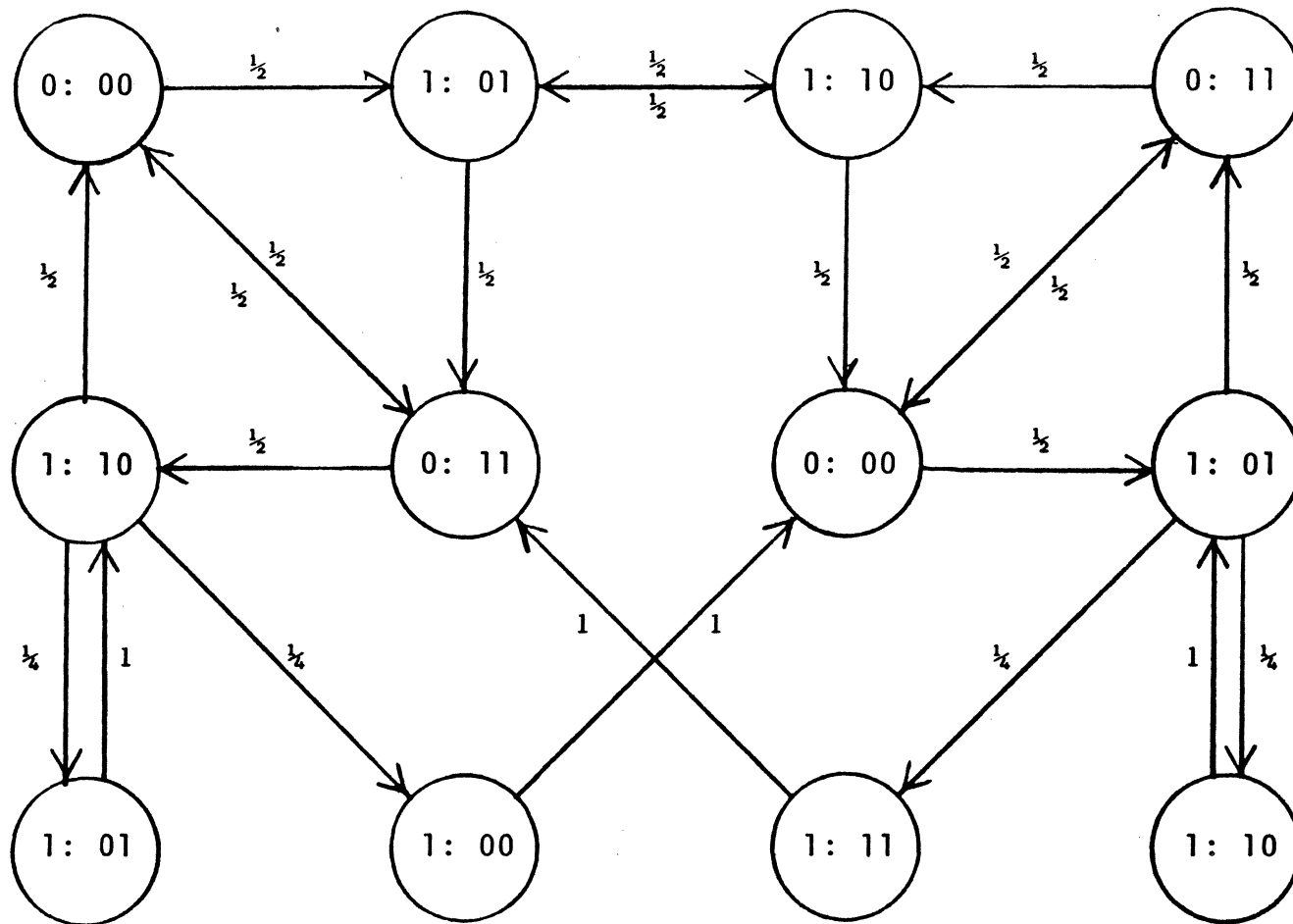
ENCODING TREE
1,7 RUN-LENGTH LIMITED CODE

T. Horiguchi & K. Morita, "An Optimization of Modulation Codes in Digital Recording," IEEE Trans. Mag. V. MAG-12, Nov. 1976, pp 740-42.

has
dc component



DC-FREE MODIFICATIONS OF MILLER-MFM CODE



ENCODING STATE DIAGRAM

MILLER² CODE

CHANNEL CODE PARAMETERS

T DATA BIT TIME INTERVAL

m # OF DATA BITS GROUPED

n # OF CODE BITS IN GROUP

m/n RATE

d MINIMUM # OF ZEROS BETWEEN ONES

k MAXIMUM # OF ZEROS BETWEEN ONES

$T_{\min}$ MINIMUM TIME BETWEEN TRANSITIONS

$T_{\max}$ MAXIMUM TIME BETWEEN TRANSITIONS

DR DENSITY RATIO = $T_{\min}/T = \frac{\text{DATA DENSITY}}{\text{MAX. TRANS. DENSITY}}$

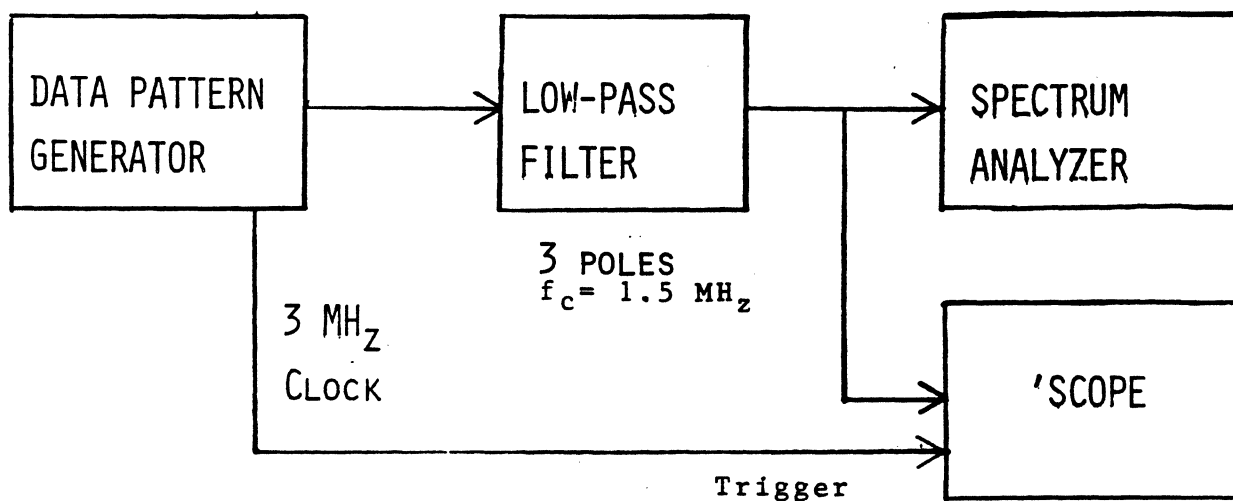
W WINDOW = $(m/n)T$

DSV MAXIMUM DIGITAL SUM VARIATION - Dc level of the code

W.D. Huber, "Selection of Modulation Code Parameters for Maximum Linear Density," IEEE Trans. Mag. V. MAG-16, Sept. 1980, pp 637-39.

	m	n	RATE	d	k	$T_{\min}$	$T_{\max}$	DR	W	CLOCK	DSV
NRZI	1	1	1	0	∞	T	∞	1	T	1/T	∞
DOUBLE FREQUENCY	1	2	1/2	0	1	T/2	T	1/2	T/2	2/T	T
MILLER MFM	1	2	1/2	1	3	T	2T	1	T/2	2/T	∞
ZM	1	2	1/2	1	3	T	2T	1	T/2	2/T	3T/2
MILLER ²	1	2	1/2	1	5	T	3T	1	T/2	2/T	3T/2
3PM	3	6	1/2	2	7	3T/2	4T	3/2	T/2	2/T	∞
2,7 RLL	2 3 4	4 6 8	1/2	2	7	3T/2	4T	3/2	T/2	2/T	∞
1,7 RLL	2 4	3 6	2/3	1	7	4T/3	16T/3	4/3	2T/3	3/2T	∞

CHANNEL-CODE COMPARISON



EXPERIMENTAL SETUP

db
10db/div



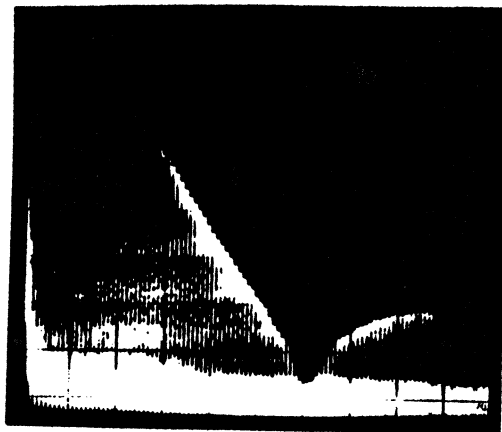
FILTER
TRANSFER
FUNCTION

UNFILTERED
3 MBIT/SEC
63 BIT PRBS

0 Frequency 5 MHz

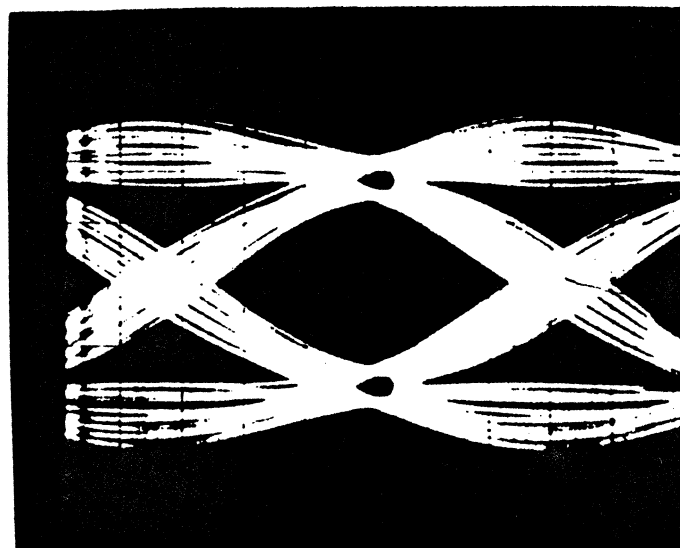
SPECTRA

CHANNEL-CODE COMPARISON TEST



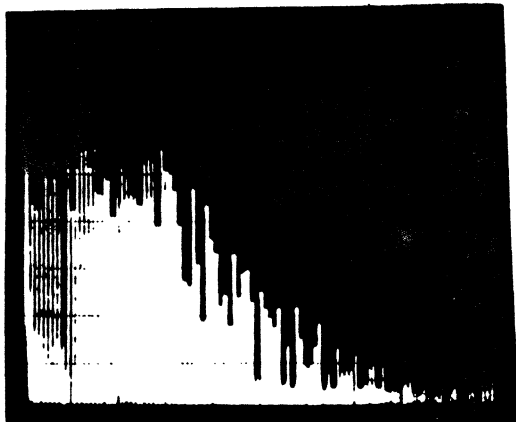
SPECTRUM

NRZI CODE

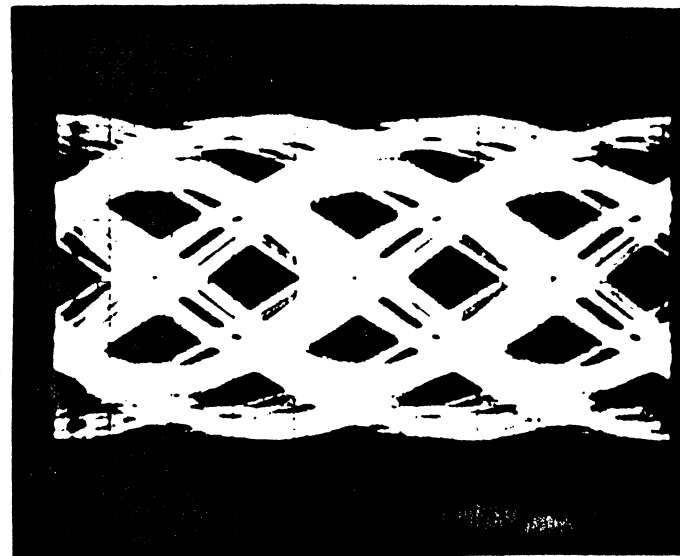


↑
EYE
↑
edge
↑
edge
of bit cell

→ spread
in 70%
(8155) 100%



SPECTRUM



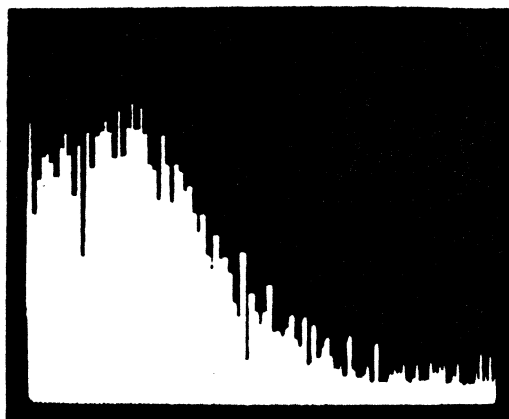
EYE

MILLER

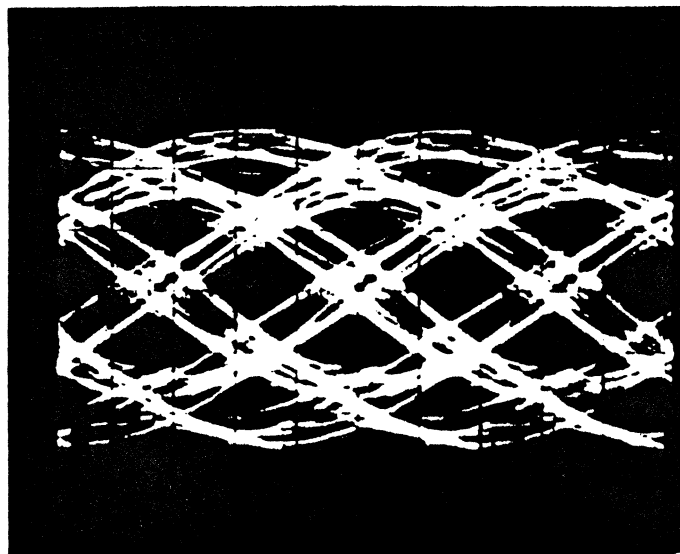
MFM

DELAY MODULATION

CODE



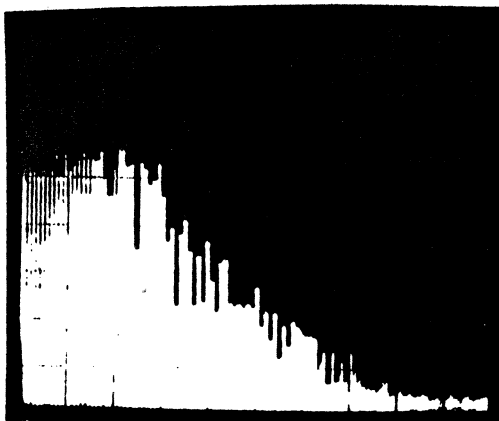
SPECTRUM



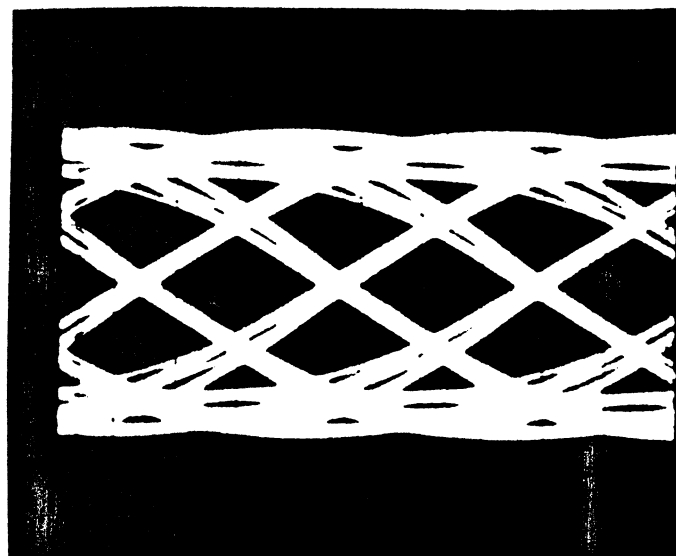
EYE

MILLER² CODE

bandwidth is reduced to 1/2

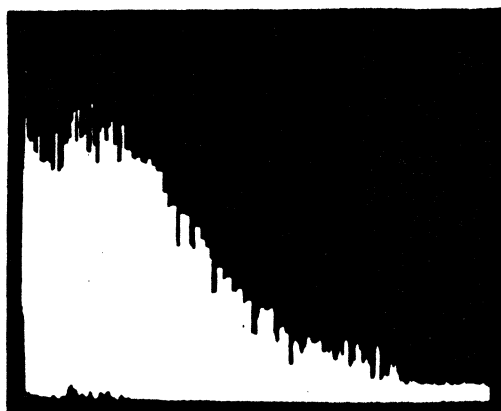


SPECTRUM



EYE

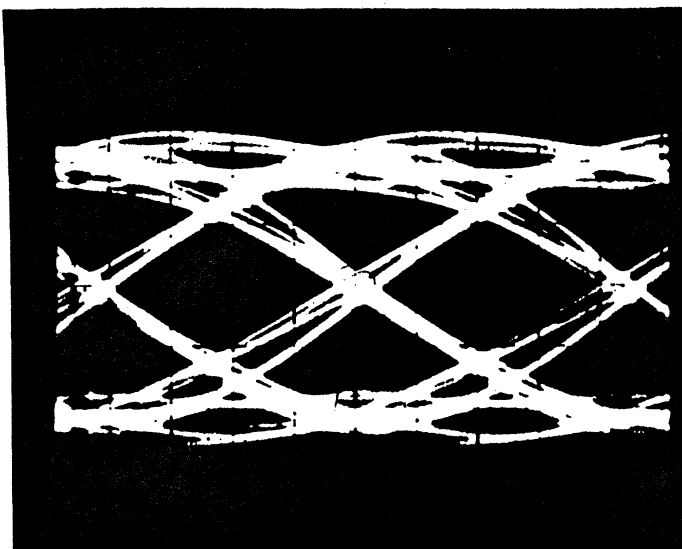
2,7 RLL CODE



SPECTRUM

1,7 RLL CODE

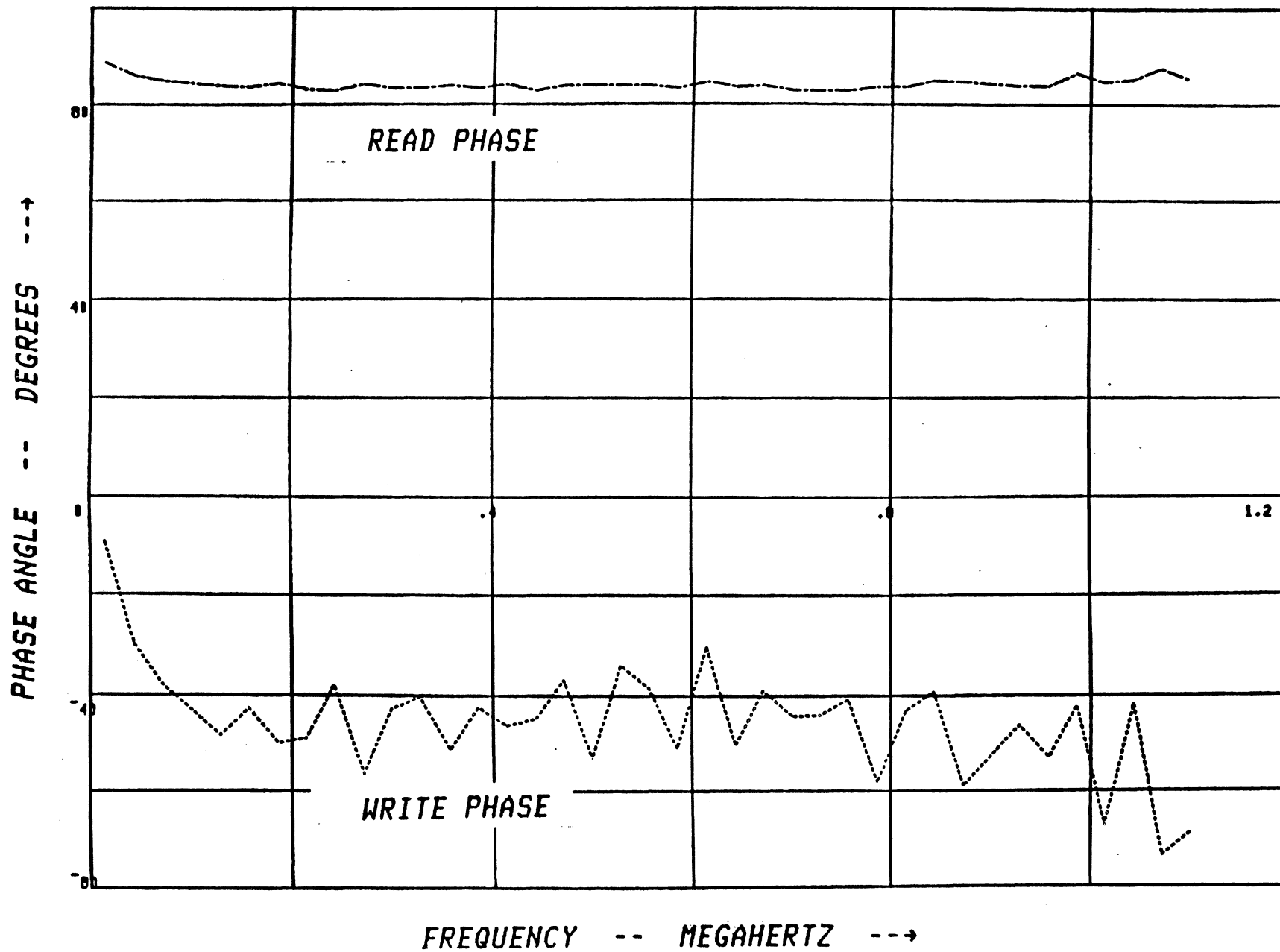
window is defined

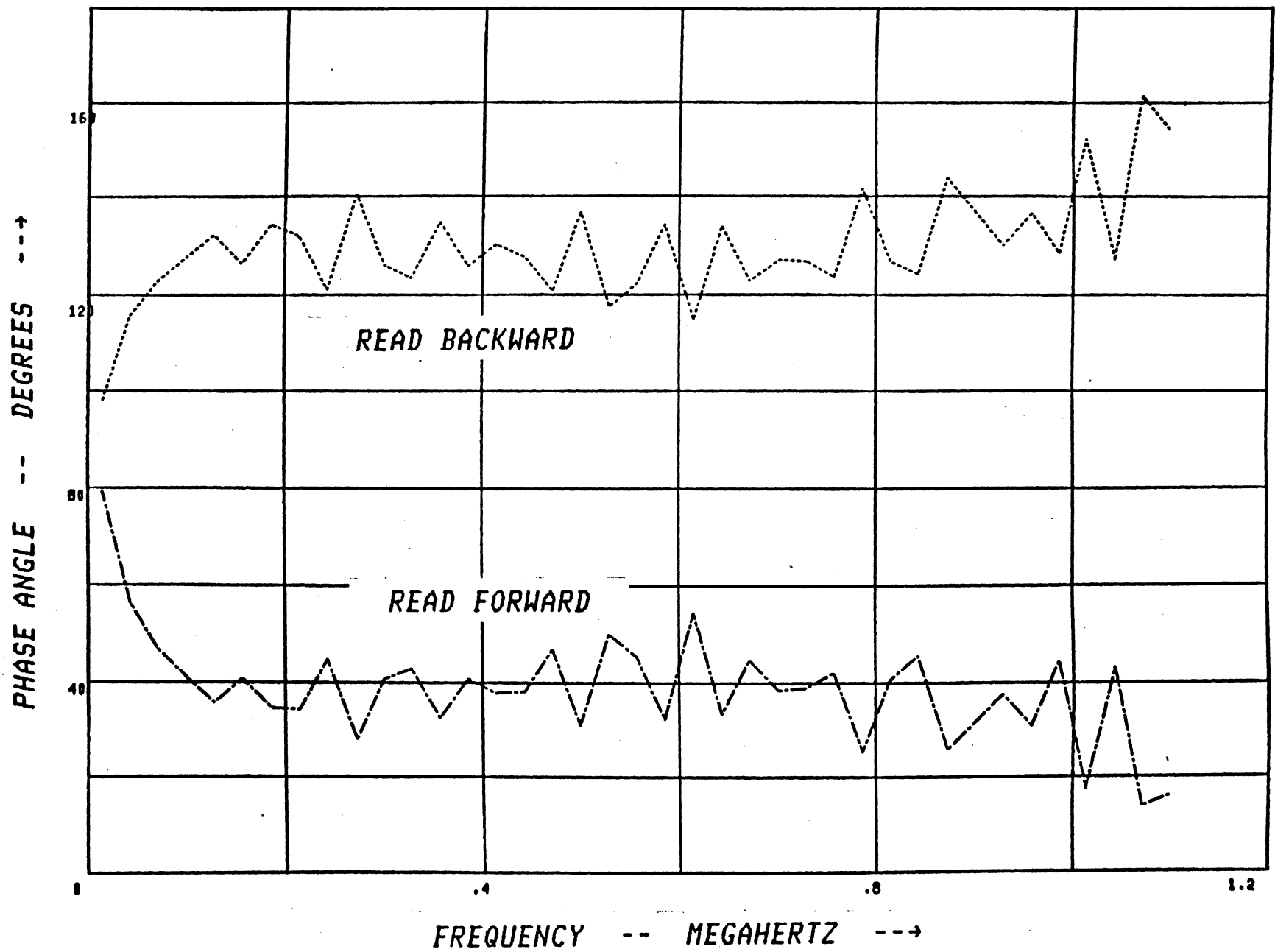


EYE

small zero signal

6-14 (a)

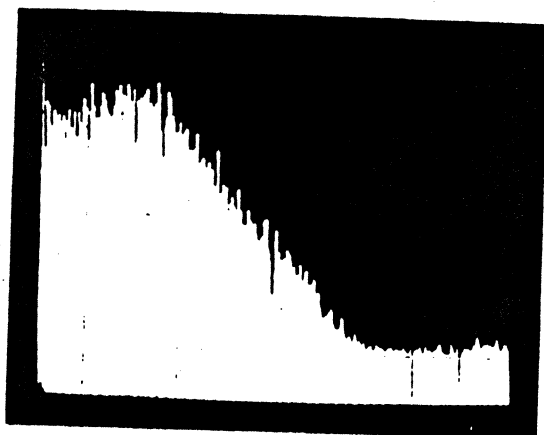




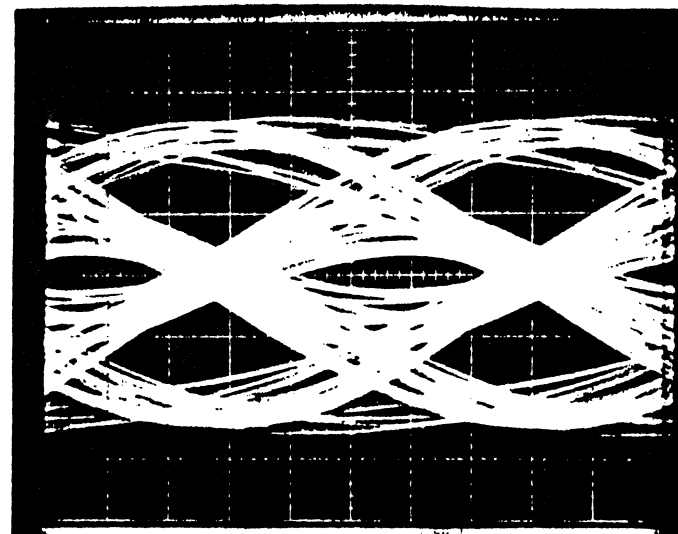
CODE	DATA BITS <i>m</i>	CODE BITS <i>n</i>	RATE	<i>d</i>	<i>k</i>	T_{MIN}	T_{MAX}	DR	W	CLOCK	DSV
NRZI	1	1	1	0	∞	T	∞	1	T	1/T	∞
DOUBLE FREQUENCY	1	2	1/2	0	1	T/2	T	1/2	T/2	2/T	T
MILLER MFM	1	2	1/2	1	3	T	2T	1	T/2	2/T	∞
MILLER ²	1	2	1/2	1	5	T	3T	1	T/2	2/T	3T/2
GCR <i>Group code recording</i>	4	5	0.8	0	2	0.8T	2.4T	0.8	0.8T	5T/4	∞
0,3 9/10	9	10	0.9	0	3	0.9T	3.6T	0.9	0.9T	10T/9	∞
1,7 RLL	2 4	3 6	0.667	1	7	1.333T	5.333T	4/3	0.667T	3T/2	∞
2,7 RLL	2 3 4	4 6 8	0.5	2	7	1.5T	4T	3/2	0.5T	2/T	∞
3,11 RLL	2 4 6	5 10 15	0.4	3	11	1.6T	4.8T	8/5	0.4T	5T/2	∞

CHANNEL-CODE COMPARISON

6 48 (a)

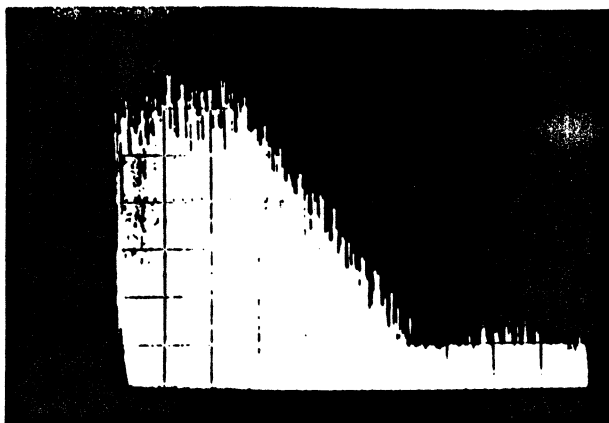


SPECTRUM

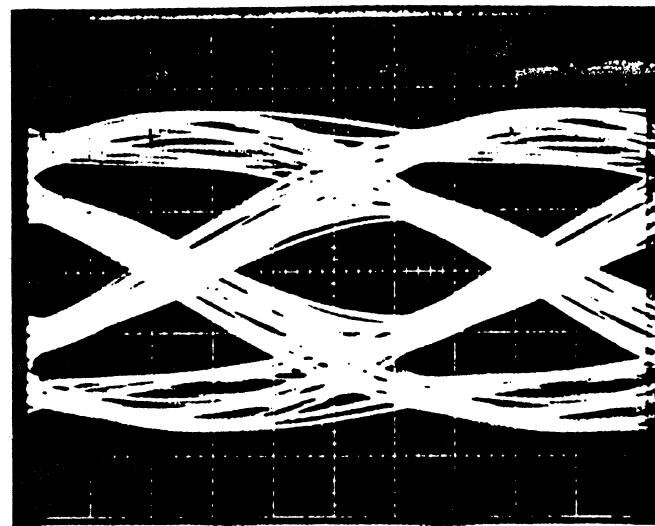


EYE

GCR --- 4/5 GROUP CODE RECORDING

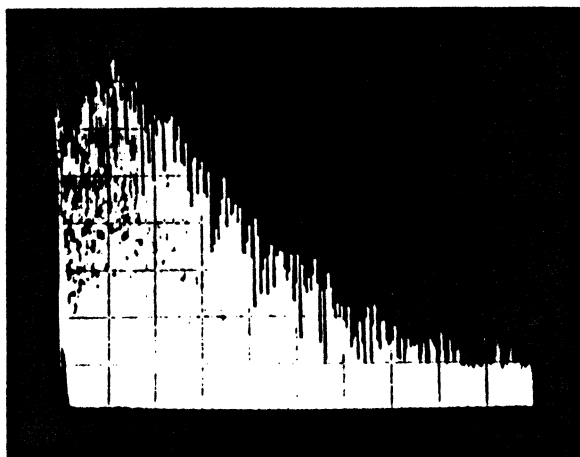


SPECTRUM

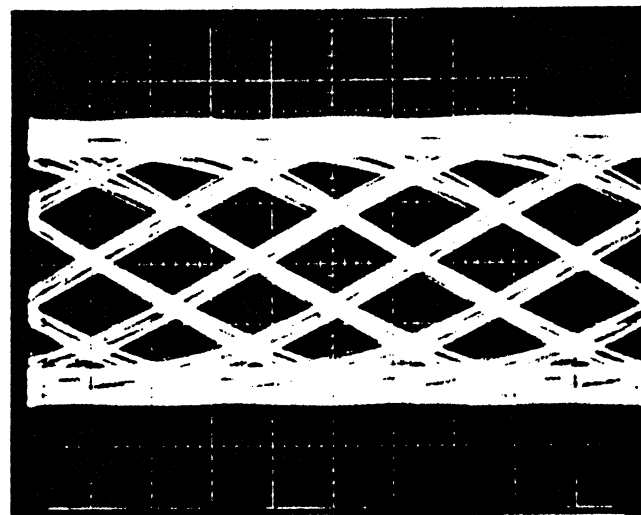


EYE

0,3 9/10THS CODE



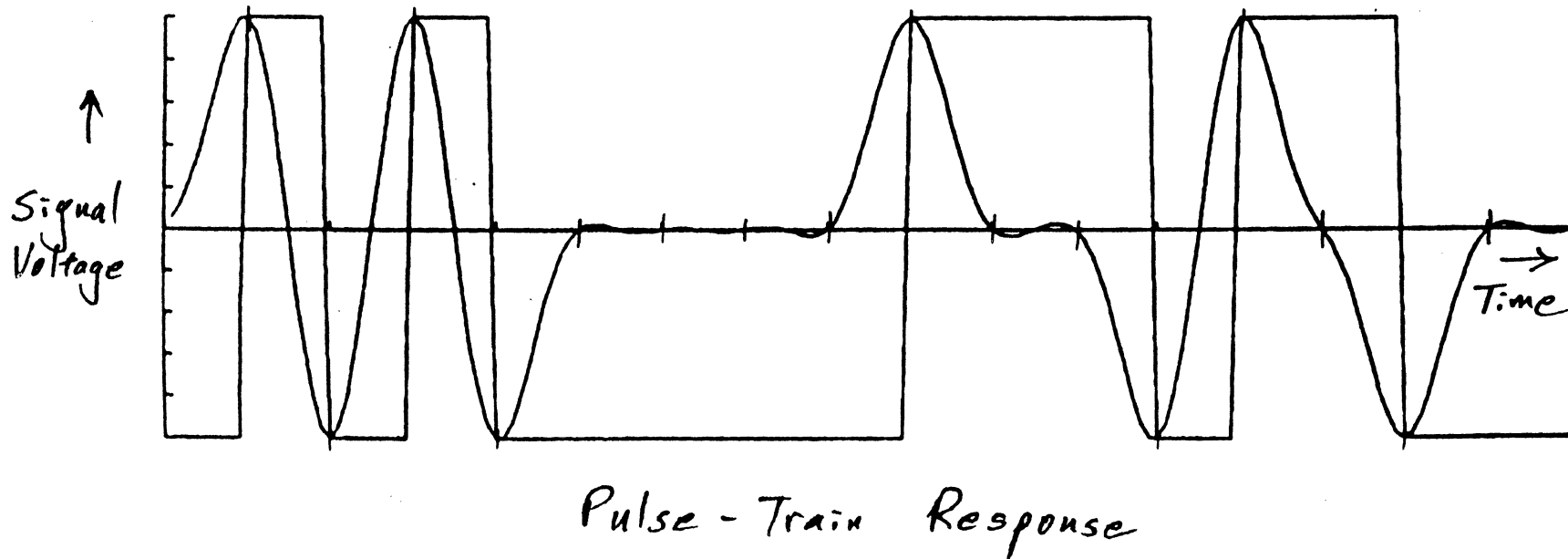
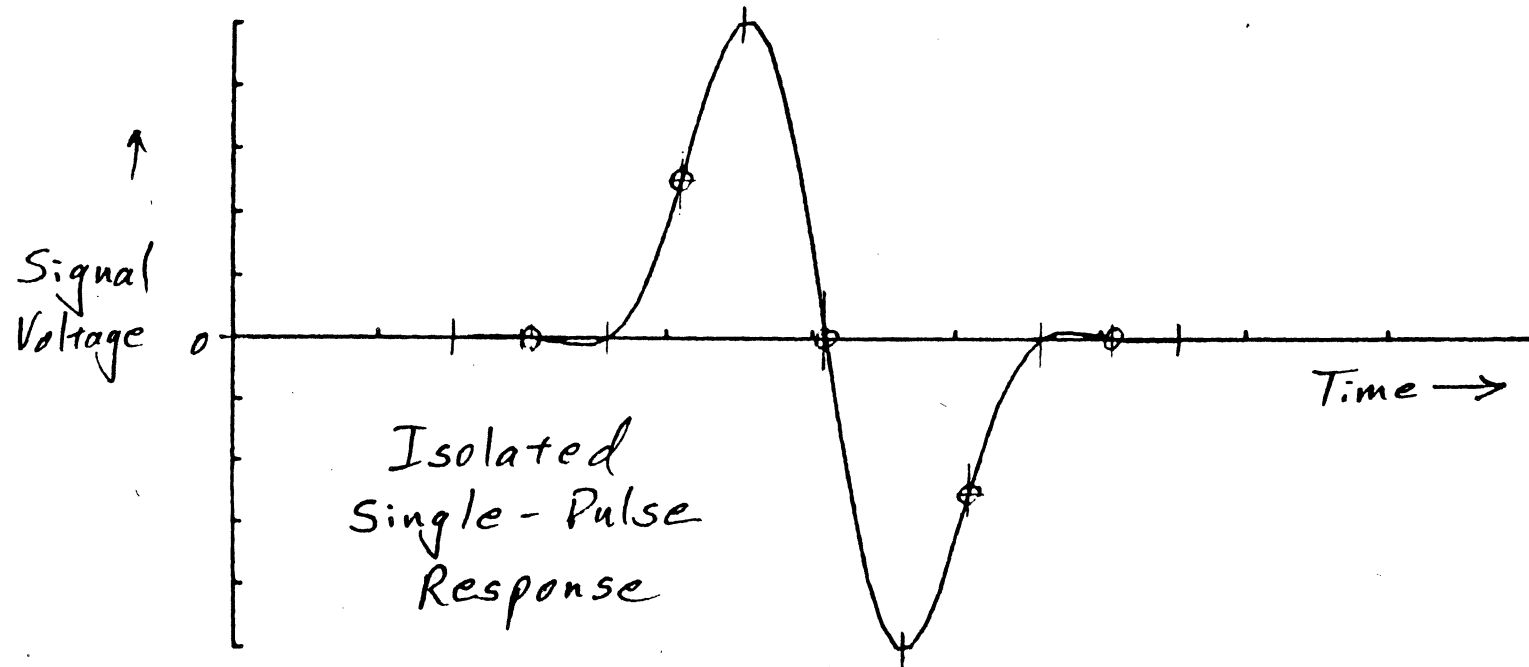
SPECTRUM



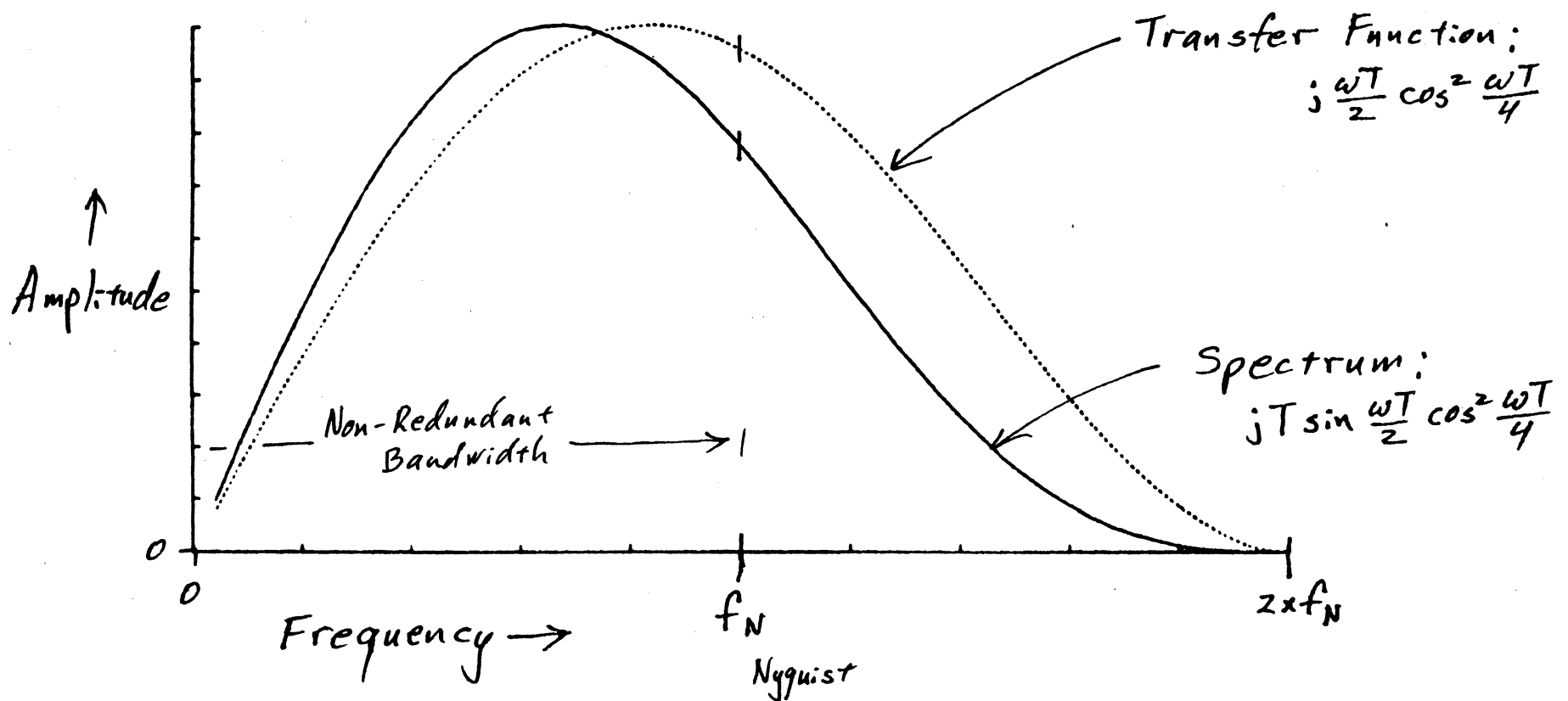
EYE

3,11 RLL CODE

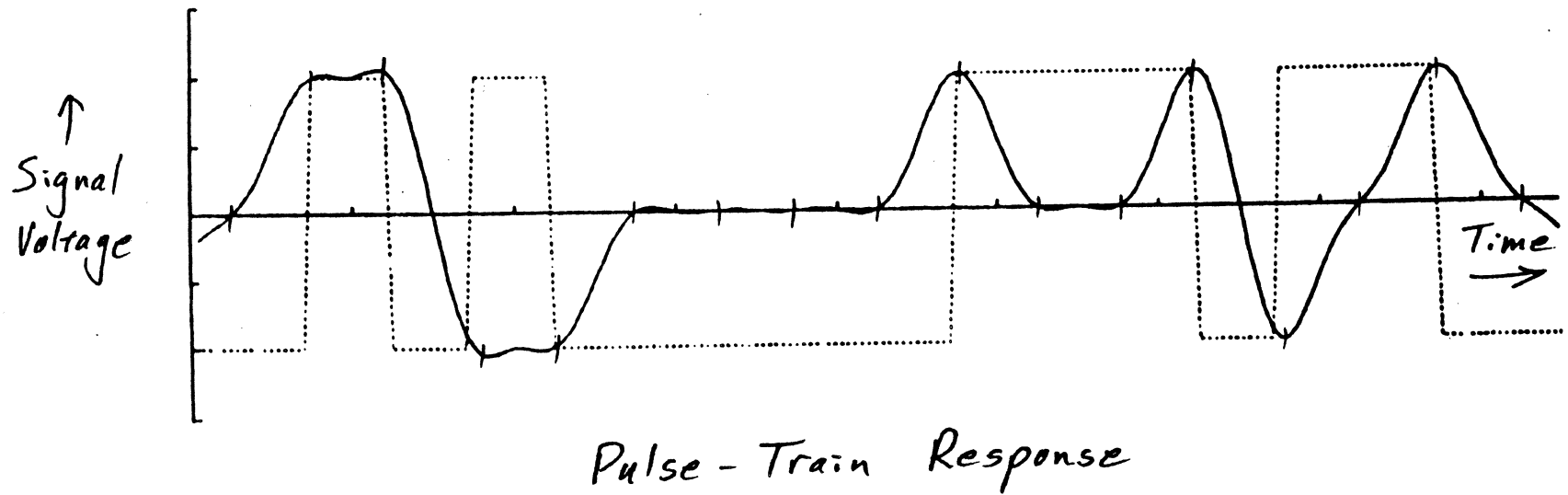
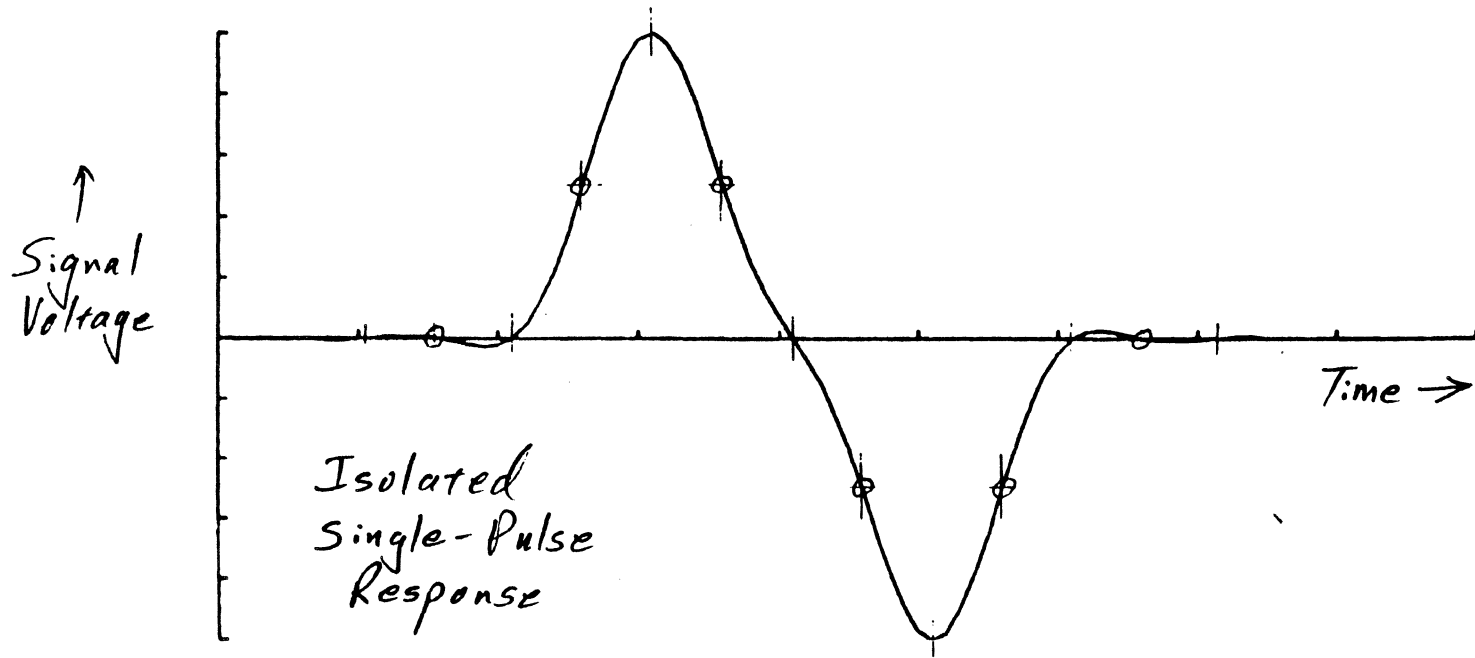
PSEUDO-TERNARY NRZI CHANNEL



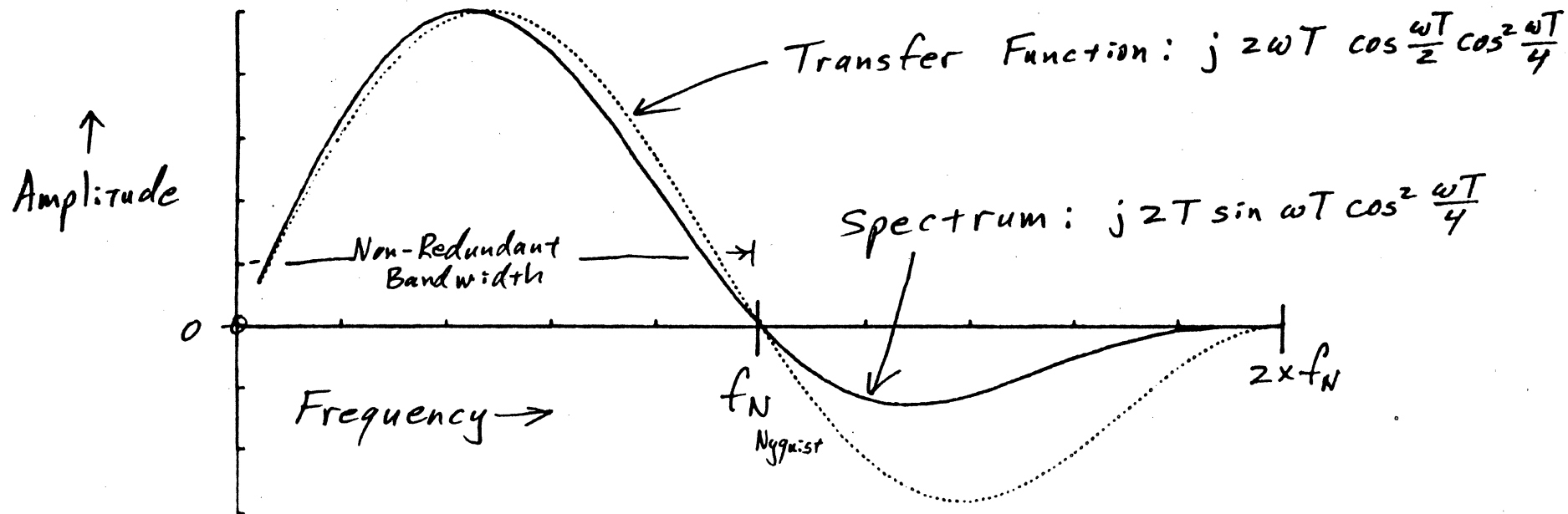
PSEUDO-TERNARY NRZI CHANNEL



INTERLEAVE NRZI

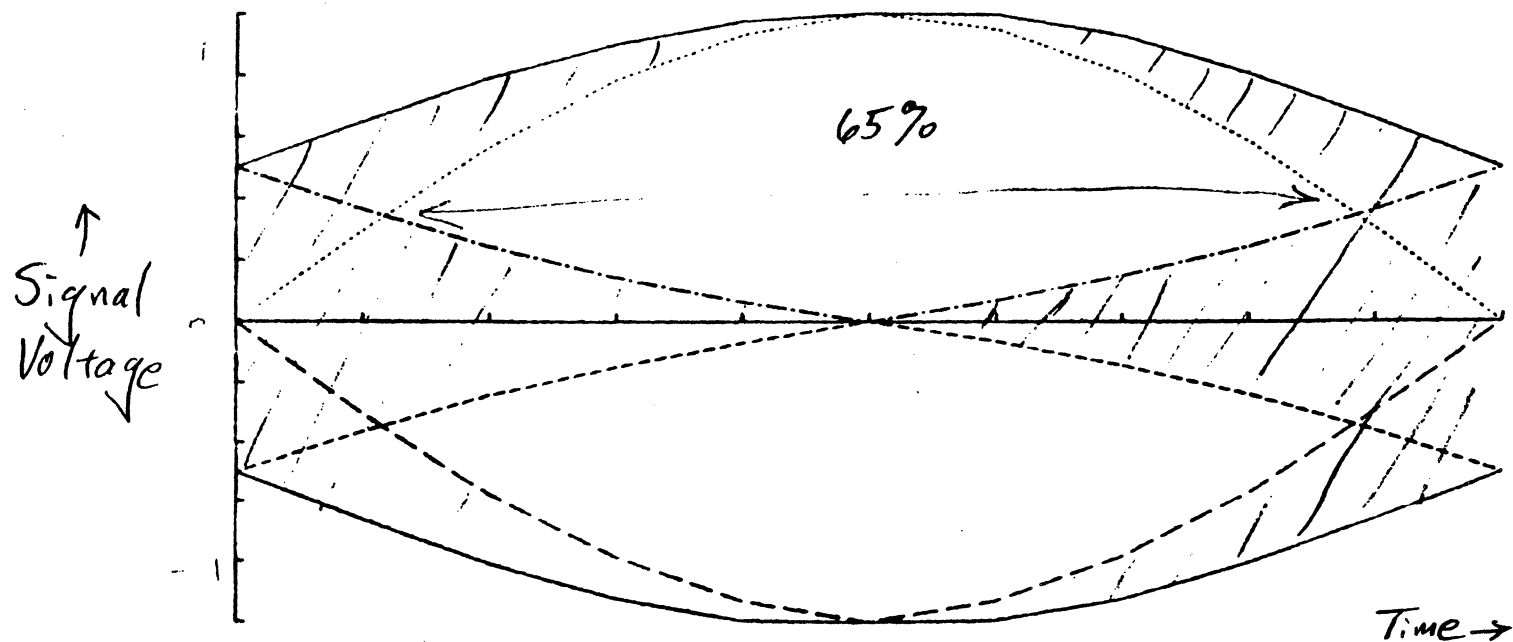


INTERLEAVED NRZI



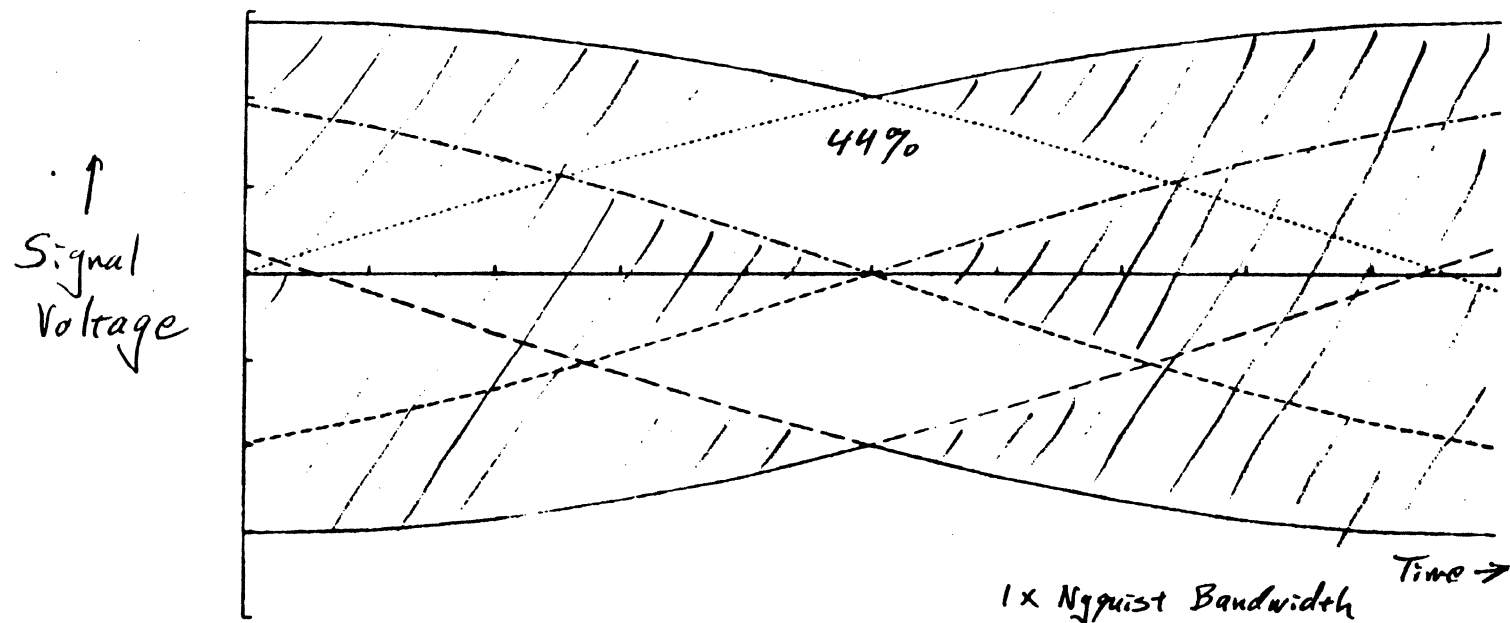
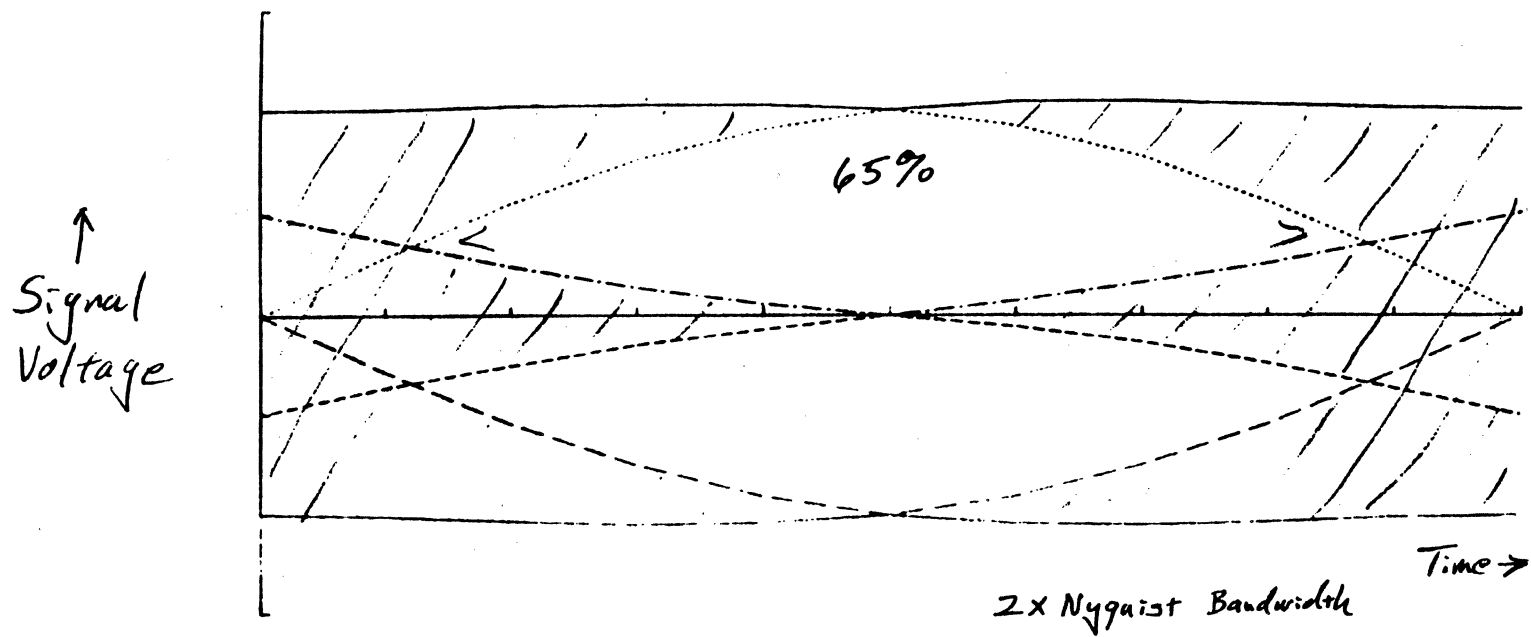
EYE PATTERN

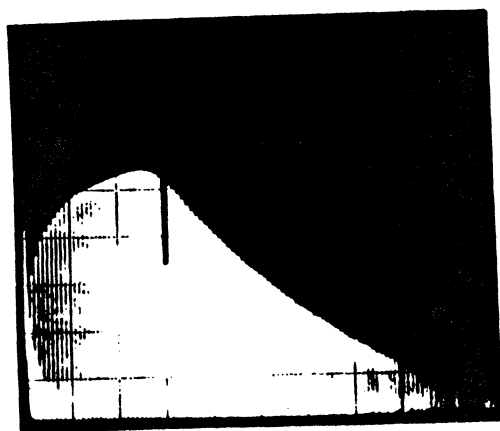
PSEUDO-TERNARY NRZI



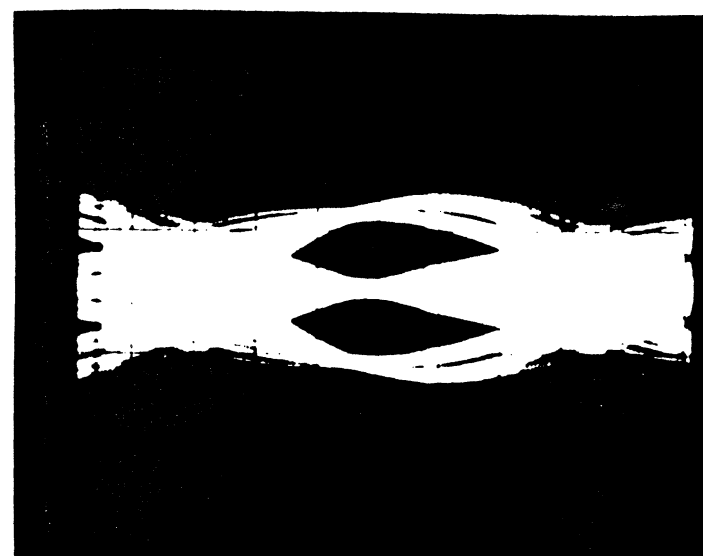
EYE PATTERNS

INTERLEAVED NRZI





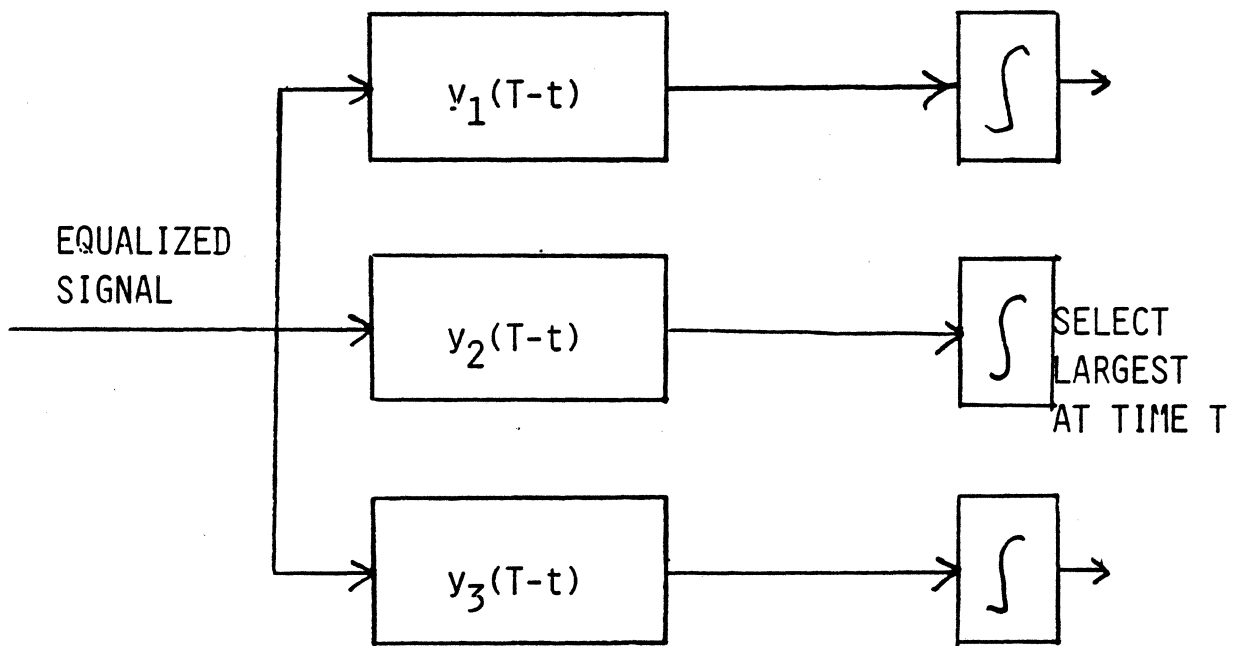
SPECTRUM



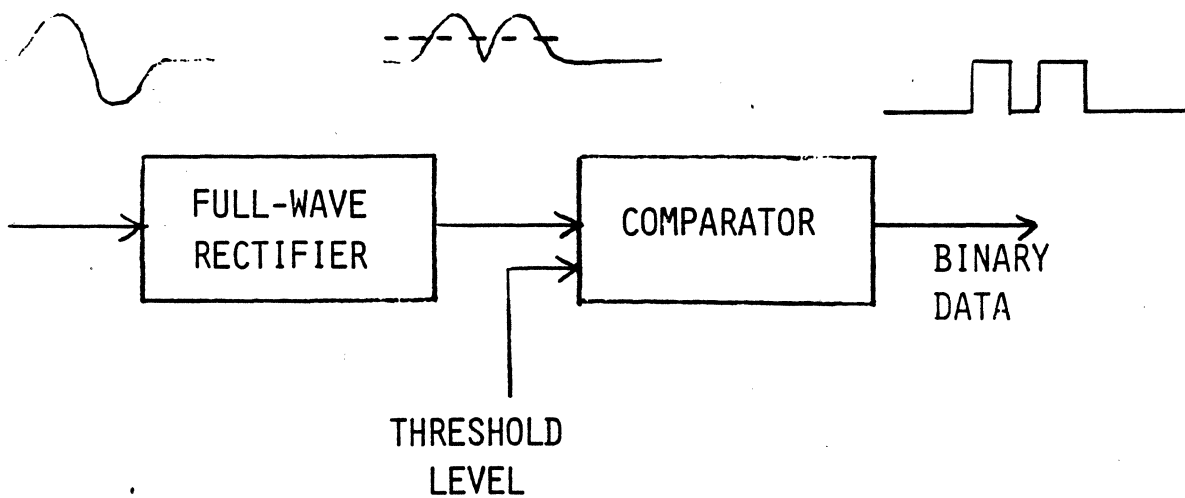
EYE

FREQUENCY MODULATION CODE

DATA DETECTORS

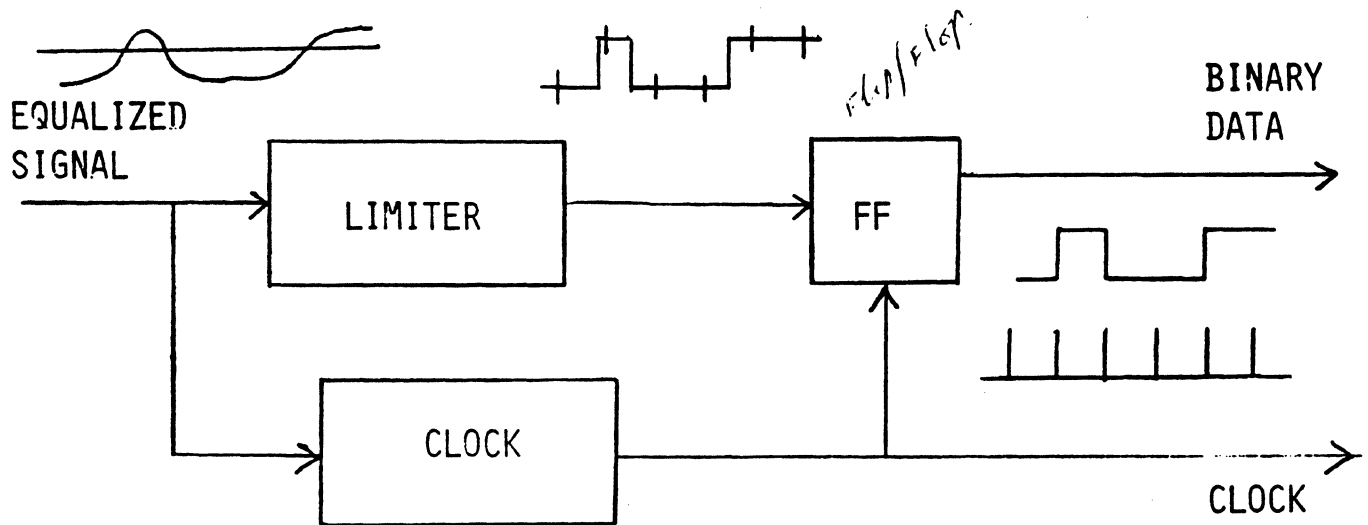


MATCHED FILTER DETECTOR

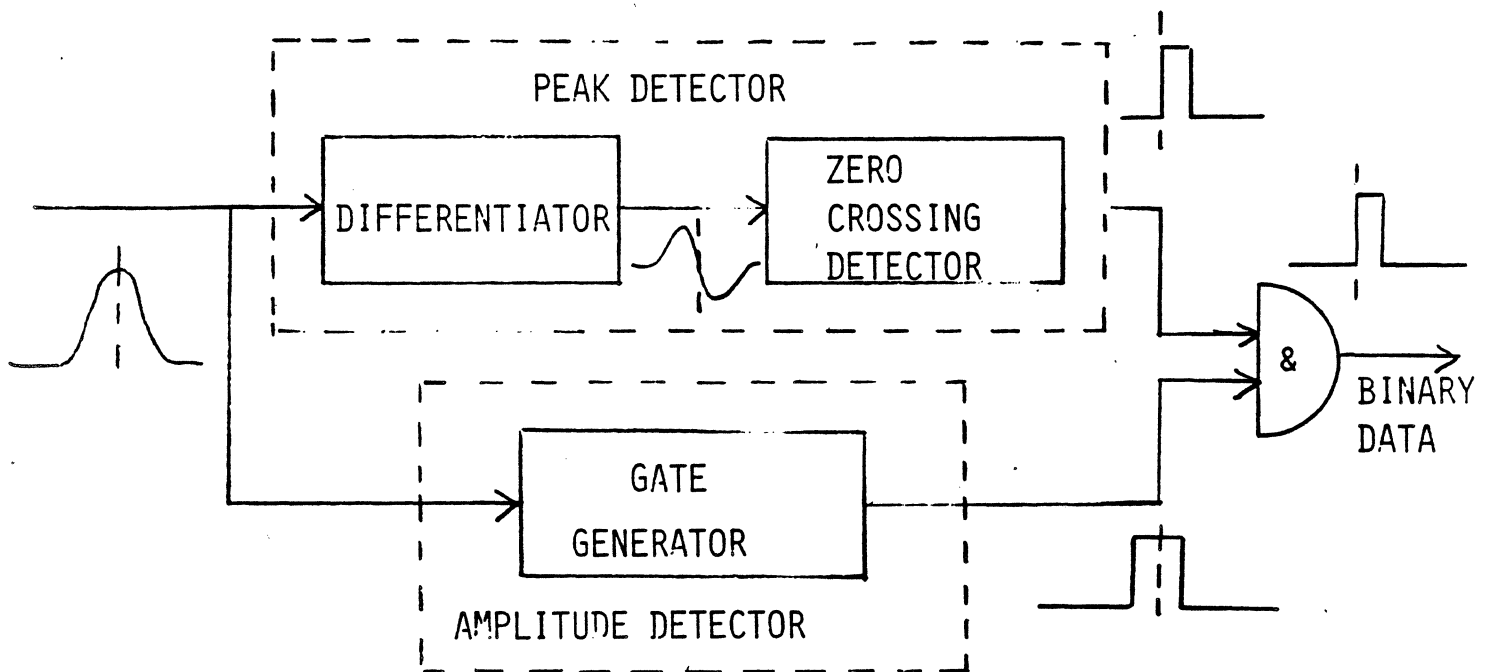


SIMPLE AMPLITUDE DETECTOR

DATA DETECTORS



SAMPLING DETECTOR



GATED PEAK DETECTOR

CLOCK RECOVERY

NRZI

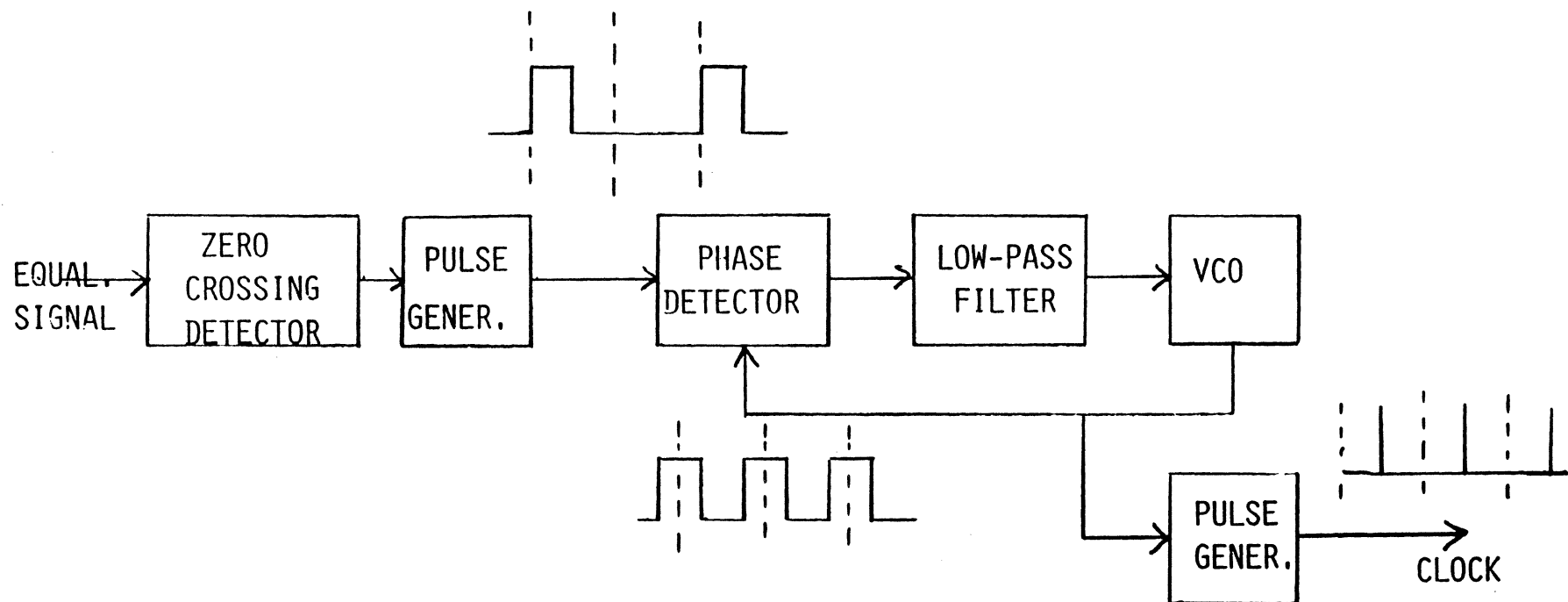
PARALLEL TRACKS, ODD PARITY
SYNCHED NRZI, ENRZI

SELF-CLOCKING CODES
DOUBLE FREQUENCY

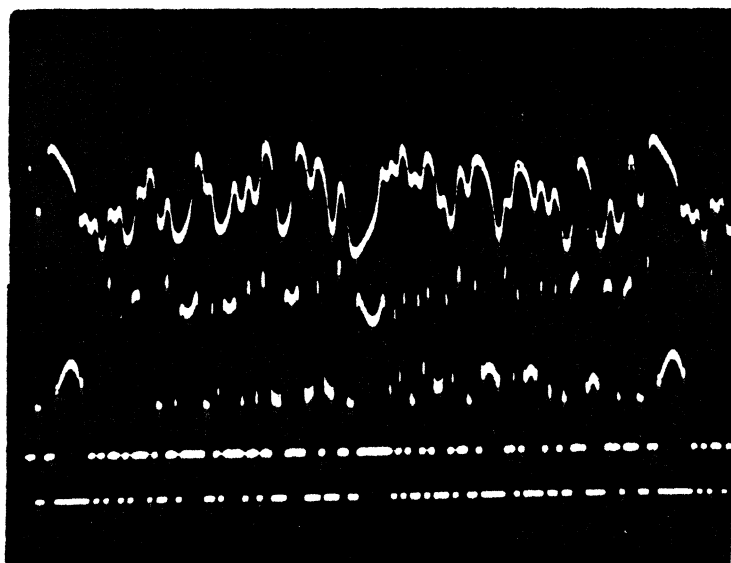
RUN-LENGTH-LIMITED CODES

FILLED CODES

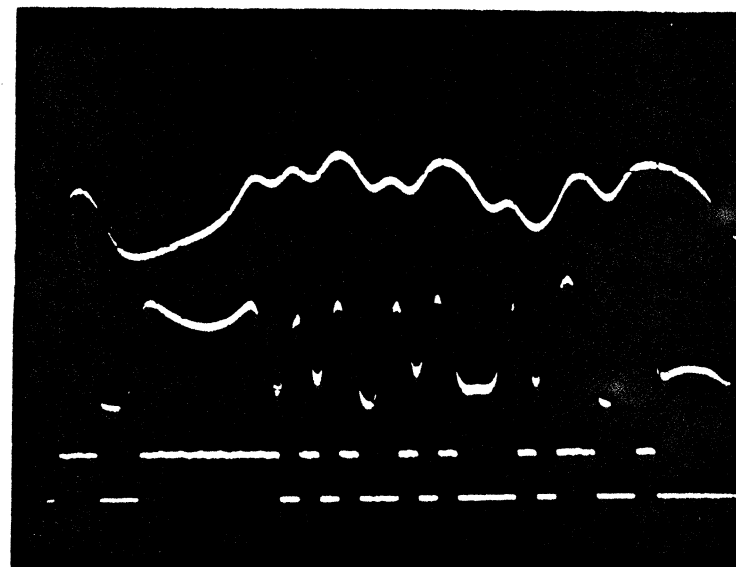
PILOT TONES



CLOCK EXTRACTION BY PHASE-LOCKED LOOP



PREAMP.
EQUALIZED
DETECTED
DIGITAL
DATA



DIGITAL RECORDING WAVEFORMS AT 60 KFCI

BELL & HOWELL INSTRUMENTATION RECORDER
FERRITE HEADS, 50 MIL TRACK
DUPONT CROLYN VIDEO TAPE

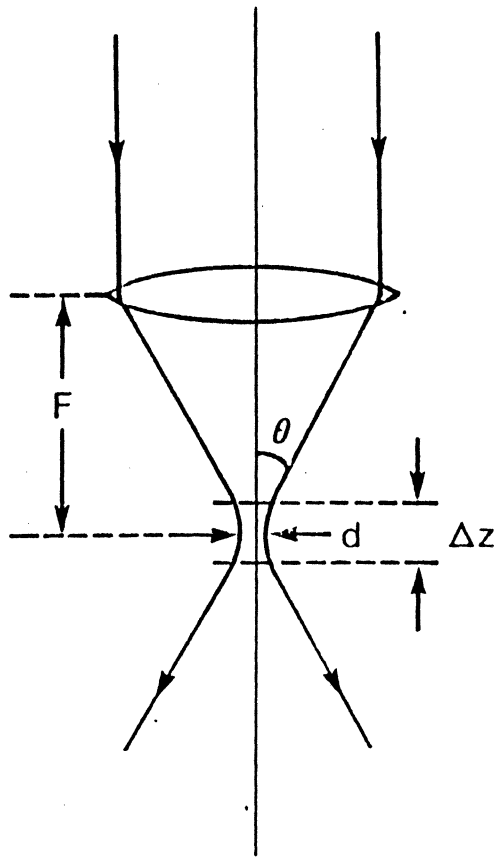
Optical Recording and Storage Media

Allan Bell
IBM Corporation

Outline

- Magnetic data storage — a moving target
- Limits on density, magnetic and optical
- Optical data storage
 - Read-only systems and media
 - Read/write systems
 - Write-once media types
 - Erasable media types
- Summary

Read/Write Spot Formation



- Diffraction limited spot-size

$$d \sim \frac{1}{2} \frac{\lambda}{\sin \theta}$$

Typically $d \approx 1.0 \mu$ for $\lambda = 820 \text{ nm}$

$\Rightarrow$ Power density $\sim 10^6 \text{ W/cm}^2!$ *10 mW laser*

- Focal length, $F \sim 1\text{-}2 \text{ mm}$

$\Rightarrow$ Large Head/Disk separation

- Depth of focus

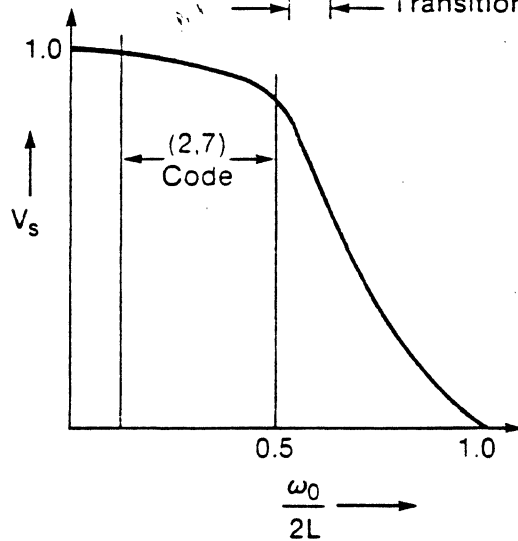
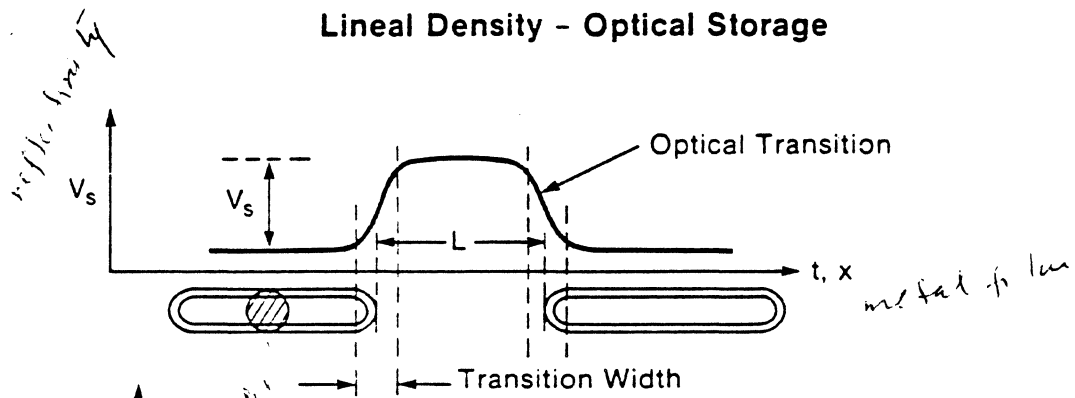
$$\Delta z \sim \frac{d}{2 \sin \theta}$$

Typically $\pm 1 \mu$

numerical aperture

as we decrease λ we have less depth of focus.

Lineal Density - Optical Storage



- Read Beam Diameter (FWHM)

$$\omega_0 = \frac{0.56\lambda}{NA}$$

- To limit bitshift

$$L_{\min} \sim \omega_0$$

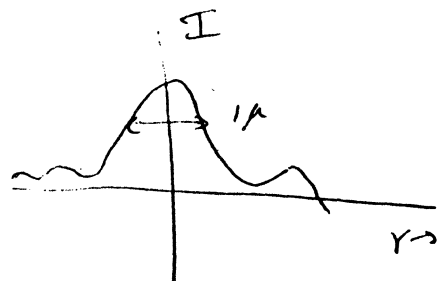
- Lineal Density $\sim \omega_0^{-1}$ TRPI

- For $\lambda = 820\text{nm}$

N.A	TRPI
0.5	27K
0.65	35K

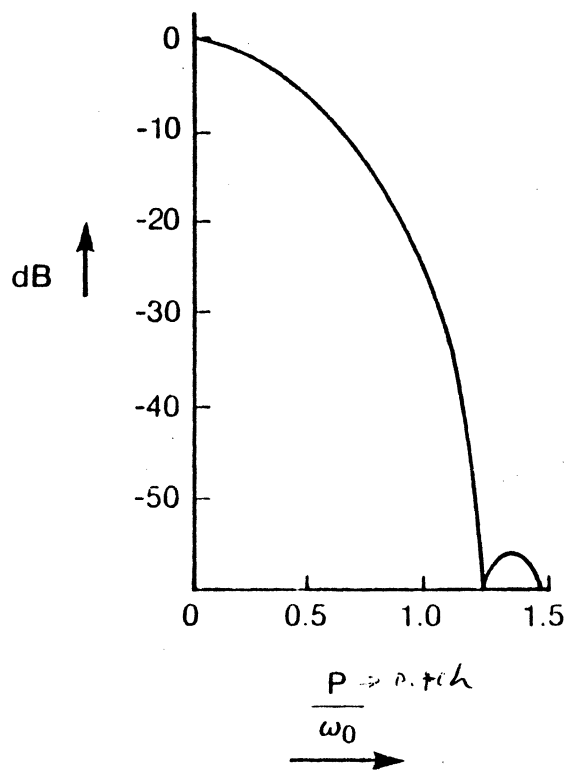
$\omega_0 \rightarrow$ nominal transition beam

TRPI $\rightarrow$ code dependent



As you increase the density, we can increase the signal by increasing the laser power.

Track Density - Optical Storage



- To Limit Crosstalk

$$\frac{P}{\omega_0} \sim 1.5 \quad \text{assuming perfect tracking.}$$

(μm)

- $\lambda = 820\text{nm}$

NA	TPI
0.5	18K
0.65	24K

- Residual error limited by:
 - centering error
 - spindle runout
 - gain-bandwidth of servo

1.67 μ V, 820 disc

DATA RATE LIMITATIONS

$$\text{DATA RATE} = \text{LINEAR BIT DENSITY} \times \text{LINEAR VELOCITY}$$

1. MAGNETIC RECORDING

- INCREASED LINEAR VELOCITY INCREASES V_s
- DATA RATE LIMITED BY ABILITY TO TRACK AT HIGH RPM;
i.e., SERVO BANDWIDTH
- 8 - 12 MB/s ANTICIPATED

2. OPTICAL RECORDING

- RECORDING RATE LIMITED BY AVAILABLE LASER POWER AND MEDIA SENSITIVITY.

CURRENT MEDIA REQUIRE ~ 25 mW CW LASER AT 3MB/s

- INCREASED DATA RATE BY USING LASER ARRAYS

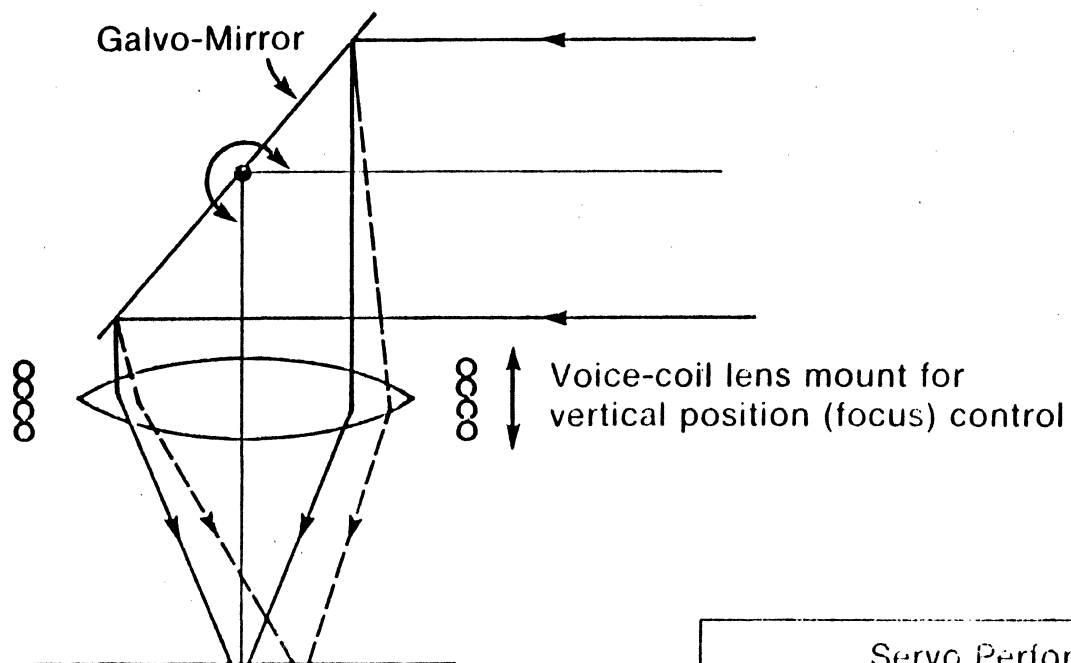
- UP TO 3MB/s x 8 = 24 MB/s ANTICIPATED

research
team

Current laser ~ 25 mW CW output
available

[30 - 100 mW demonstrated
in lab]

Read/Write Spot Positioning



Beam deflection via galvo-mirror for radial (tracking) control also permits very high speed local access (1-10ms) to adjacent tracks (± 25)

Servo Performance		
	Disk	Residual
Vertical	$\pm 0.5\text{mm}$	$\pm 0.1\mu$
Radial	$\pm 0.1\text{mm}$	$\pm 0.1\mu$

common to optical, magnetic or any other tech.

GENERIC ISSUES IN ULTRA-HIGH DENSITY

DATA STORAGE ($\geq 10^8$ bpi²)

1. FILE RESPONSE TIME

DATA CAPACITY PER ACTUATOR

ACCESS TIME AND DATA RATE

2. ECC OVERHEAD

MEDIA DEFECT DENSITY

3. MEDIA RESOLUTION AND NOISE

MARK GEOMETRY

4. SYSTEM RESOLUTION AND NOISE

POSITION SERVOMECHANISMS FOR READ/WRITE HEAD

READ/WRITE METHOD

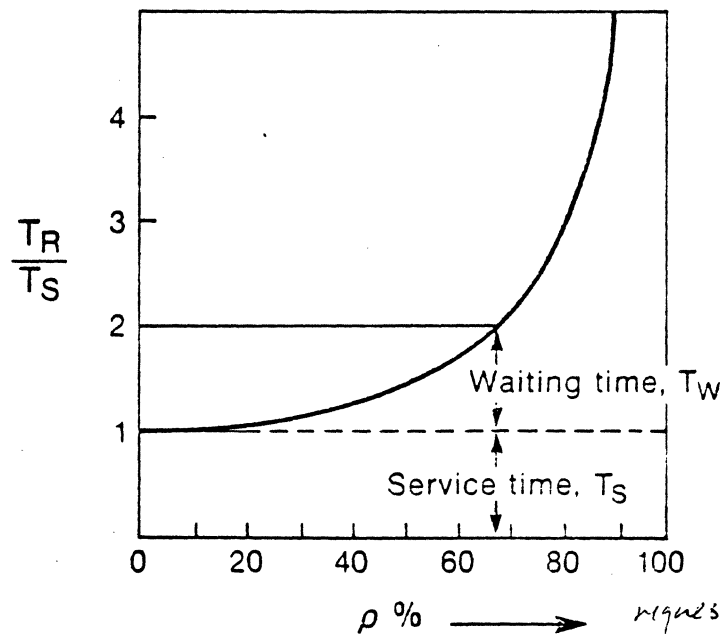
File Transfer Rate

- Service Time: $T_S = T_A + T_L + T_F$

- Response Time: $T_R = T_S + T_W$

$$\frac{T_R}{T_S} = \frac{1}{2} \left[\frac{2 - \rho}{1 - \rho} \right]$$

ρ = Actuator Utilization Duty Cycle

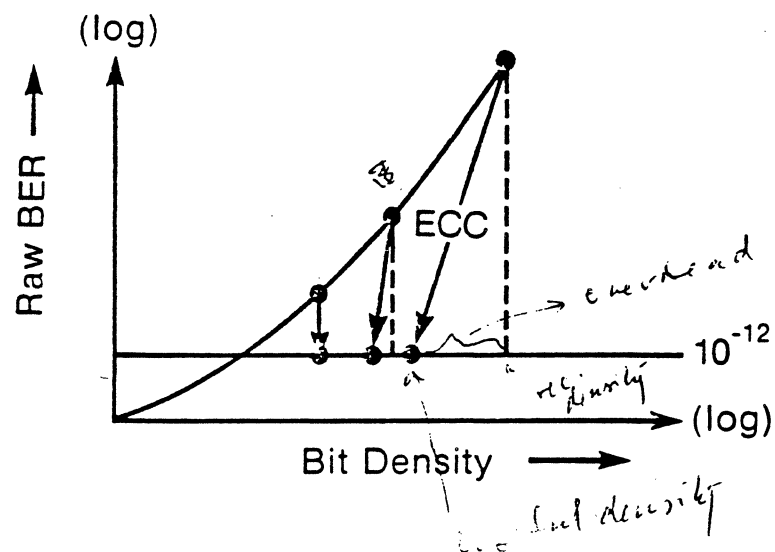


- Increased capacity per actuator leads to increased actuator utilization and an access bottleneck

$\Rightarrow$ increase # actuators or reduce disc size to maintain dynamic performance (access density)

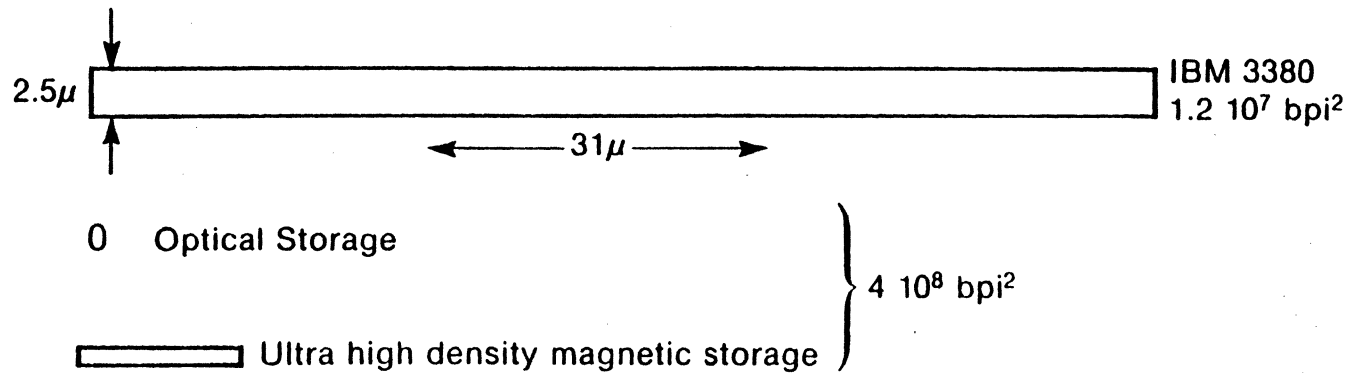
Error Control and Correction

- ECC Overhead Increases with Bit Density



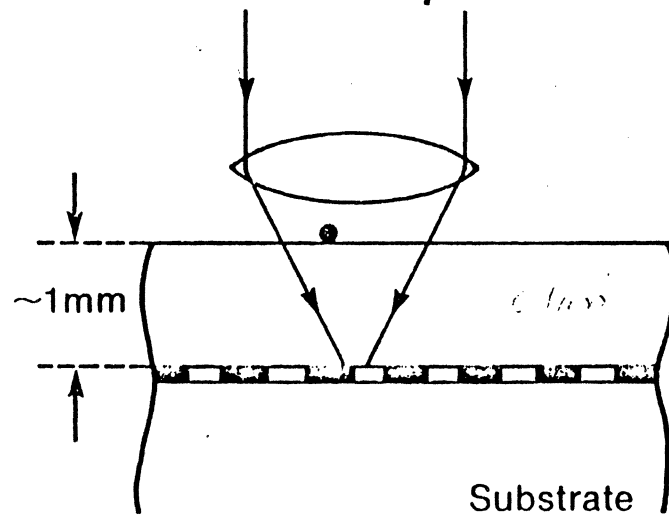
- For Density $> 10^8$ bpi²
 Raw BER 10^{-4} - 10^{-6}
 $\Rightarrow$ ECC Overhead 10-20%

Media Defect Density and Hard BER



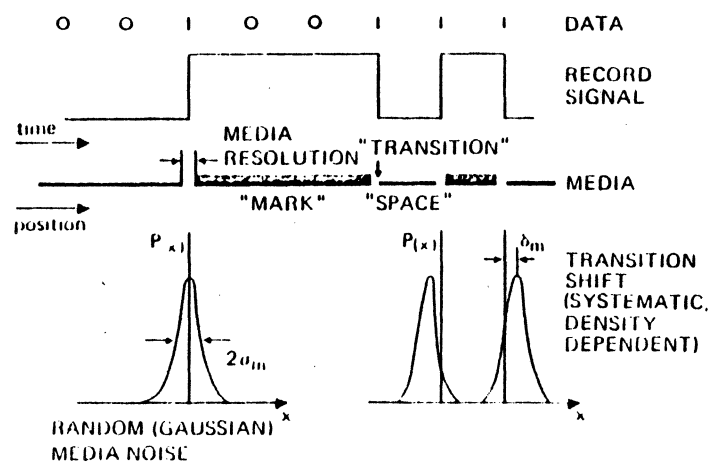
- Substrate surface and media coating must be defect free at $1 \text{ sq.}\mu$ level
 - External contaminants (dust) must be excluded from the data storage plane during specified media lifetime
 - Media must be selected and environment controlled to minimize micro-corrosion during specified lifetime
- Media selection and fabrication is an extremely critical issue for any technology

Optical Media Encapsulation

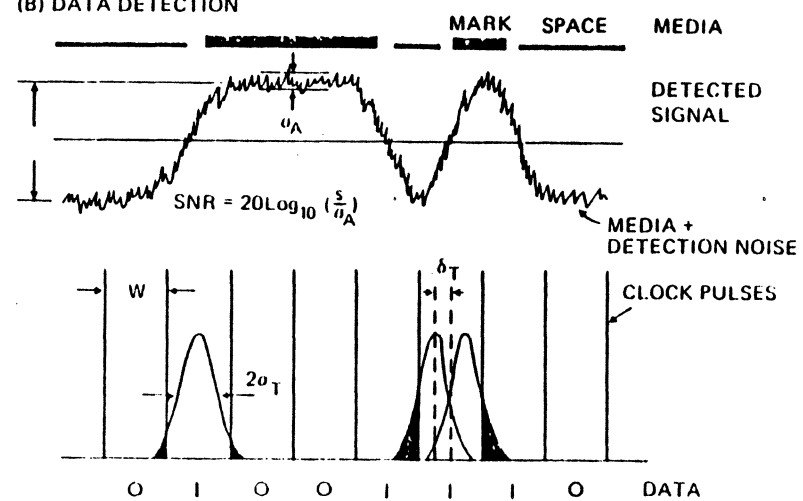


- Eliminates defects due to dust particles
- Protects storage layer from environment
- Permits removability of media → needs good service.

(A) DATA RECORDING



(B) DATA DETECTION



high performance optical storage in 7.5" (15K+PI)

SUMMARY COMPARISON OF PERFORMANCE

	MAGNETIC		OPTICAL	
	3380	ULTIMATE	MODERATE (GaAs LASER, 0.5 NA LENS)	ULTIMATE (BLUE LASER 0.85 NA LENS)
LINEAR ⁽¹⁾ DENSITY	~ 15K bPI	>40KbPI	~ 35K bPI	>80K bPI
TRACK DENSITY	>800 TPI	>3K TPI	~ 16K TPI	>40K TPI
AREAL DENSITY	12Mb/in ²	>120Mb/in ²	560Mb/in ²	>3200Mb/in ²
DATA RATE	3MB/s	~ 12 MB/s	3MB/s ⁽²⁾	6MB/s ⁽²⁾

(1) ASSUMING (2,7) CODE AT 1.5 BITS/TRANSITION

(2) X N FOR N ELEMENT ARRAY, PARALLEL RECORDING

Access density	~ 80	25	10/s/GB
Seek time	16	85-200	ms

COMPARISON OF MAGNETIC AND OPTICAL STORAGE TECHNOLOGY FACTORS

	Magnetic	Optical
Head/Disk Separation	0.1 μ	1000 μ
Substrate	Ultra-smooth Al	Al, Glass Polymer
Storage Medium	Thin Film < 1 μ	Thin Film < 1 μ
Encapsulation	No	Yes
Drive Internal Environment	Sealed HDA	Open to Ambient
Removability	No	Yes

*app
dependent
as an advantage.)*

Classification of Optical Data Storage

	Read-Only	Read/Write	
		Write-Once	Erasable
Media Type	Factory replicated plastic disk with embossed surface	Various thin film metal or organic materials	Magneto-optic or phase-change thin film materials
Media Capacity Both Sides 30 cm Disk	1 hr continuous video 100,000 video frames 1 hr digital audio* 2-8 GB Data	2-8 GB Data 20K-100K A4 doc.	1-4 GB Data
Applications	Consumer entertainment Education/training Program distribution Database distribution Videogame ROM	Document storage Archival database (tape replacement) On-line mass storage (juke-box)	High capacity, low cost store for small systems
Media Cost (†)	\$2-10/GB	\$10-50/GB	\$10-50/GB
Drive Cost (†)	\$0.5-5K	\$5-20K	\$5-20K

*12 cm disk, 1 side

† R. Durbeck IEEE MSS (1982)

commercialized

first product appearing

prototypes only so far

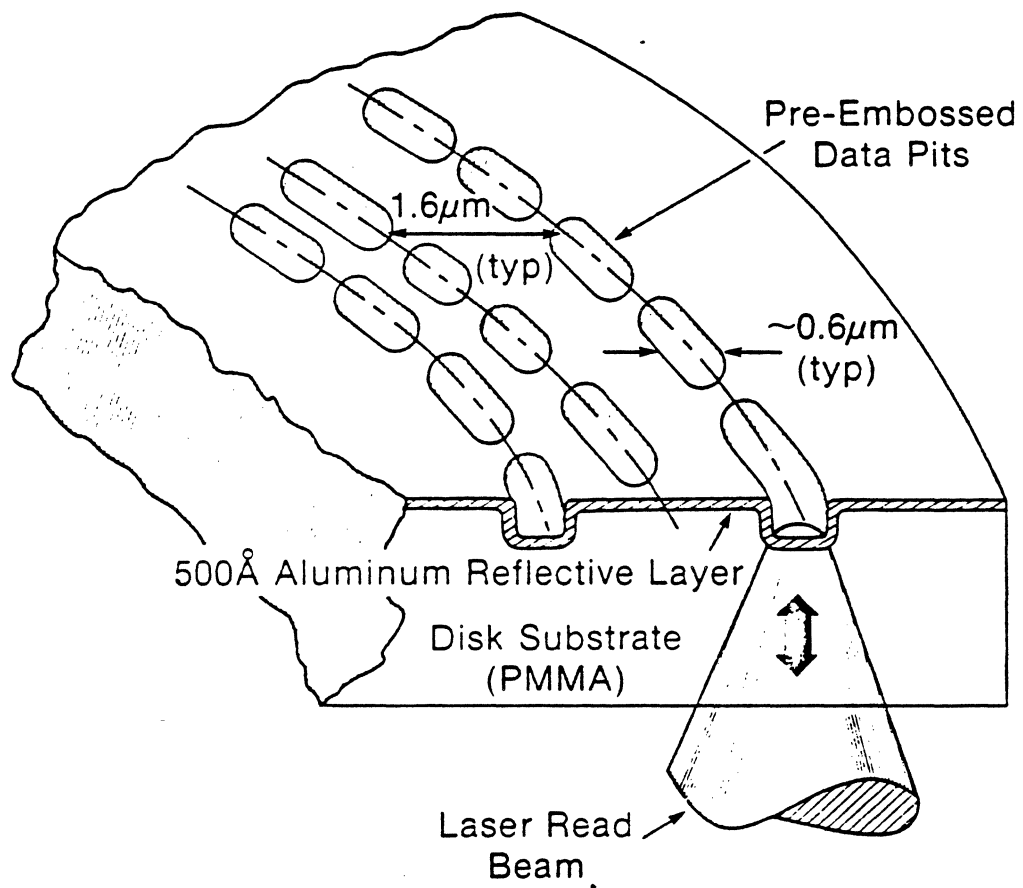
Specifications of Read-Only Optical Discs

	Video Disk	DAD <i>Audio</i>
Laser	HeNe	Semiconductor Diode
Wavelength	633.0 nm	780.0 nm
NA	0.4	0.45
Diameter	30.0 cm	12.0 cm
RPM	1800 ^a	480-210 ^b
Thickness	1.25 mm	1.2 mm
Track pitch	1.6-2.0 μ	1.6 μ
Pit depth	0.12 μ	0.12 μ
Pit width	0.4 μ	0.6 μ
Pit Length	0.5-2.0 μ	0.9-3.3 μ

^aNTSC video, constant angular velocity mode

^bConstant linear velocity mode, 1.25 m/s

Read-Only Optical Disk



PLAYBACK PRINCIPLE OF VIDEODISC

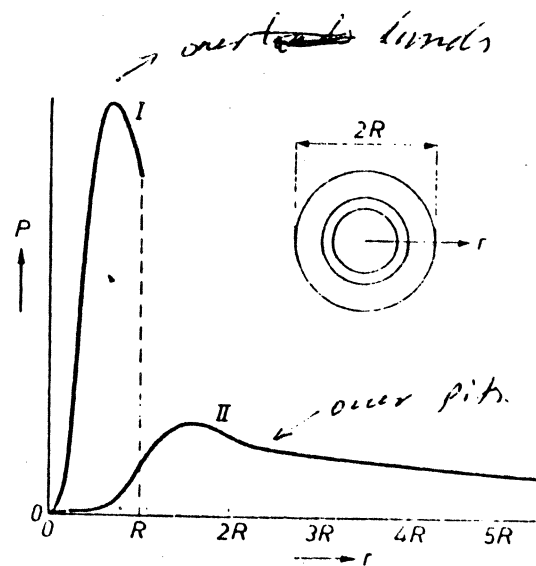
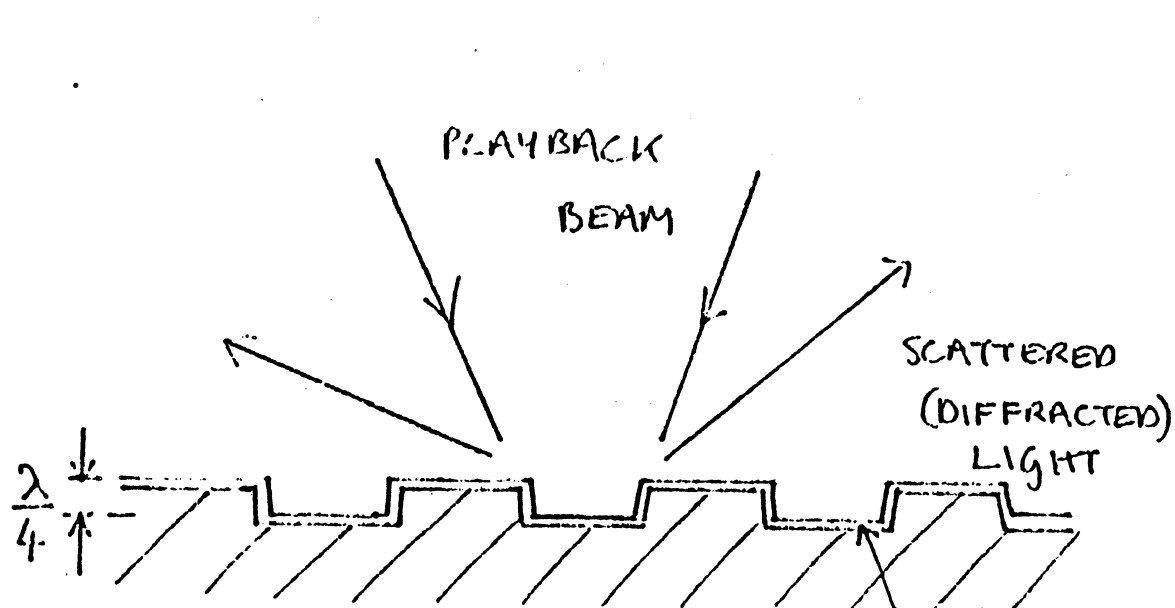
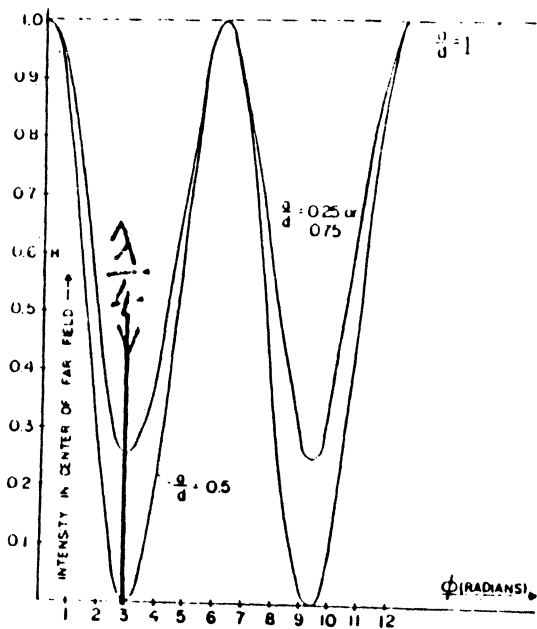


Fig. 1. The power P reflected by the surface of the record into the pupil of the objective plotted as a function of the distance r from the optical axis. Each curve shows the total power in a thin annulus of radius r . The diameter of the pupil is $2R$. Curve I represents the power for reflection from a flat part of the record, curve II the power when the spot is centred on a pit in a track in which the period of the pattern of pits is $1.5 \mu\text{m}$ and the width of the pits $0.8 \mu\text{m}$; the pitch of the track is $2 \mu\text{m}$.

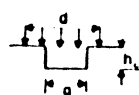
(31)

ALAN E. BELL
IBM



$$I = 1 - 4 \frac{g}{d} (1 - \frac{g}{d}) \sin^2 \left(\frac{\phi}{2} \right)$$

$$\phi = \left(\frac{2\pi}{\lambda} \right) h$$



film media thickness $\sim 1000 \text{ \AA}$

Fig. 22. On-axis intensity in far field vs. scattering depth of a rectangular pit illuminated by a rectangular beam.

(32)

SIGNAL CHARACTERISTICS

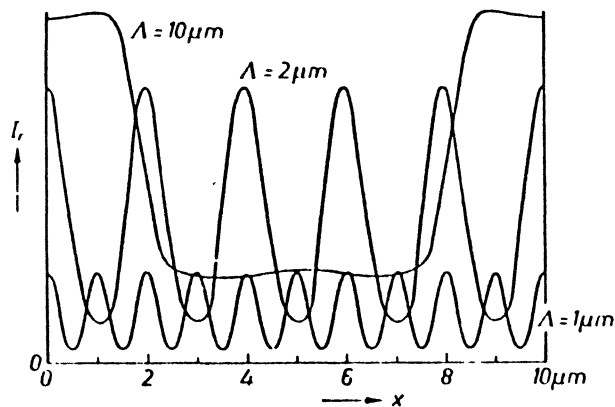


Fig. 3. Calculated modulation of the intensity I_r of the reflected light for various values of the period Λ of the pit pattern as a function of the position x on the track. $x = 0$ corresponds in all cases to a point half-way between two pits. For the purpose of the calculation the aperture of the lens used is taken as 0.4, the width of the pits as $0.8 \mu\text{m}$ and the wavelength of the light as $0.63 \mu\text{m}$.

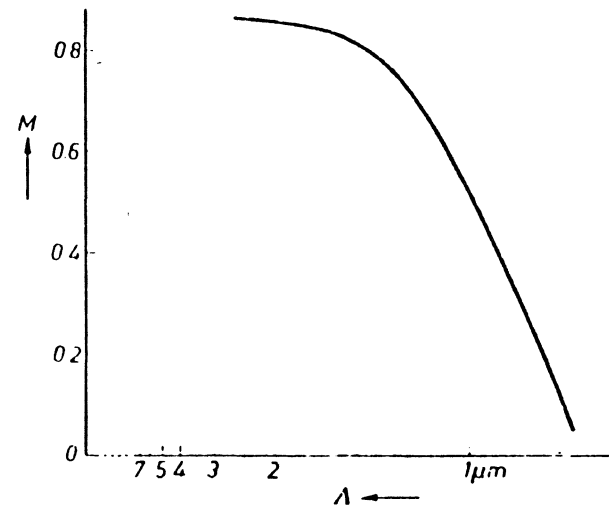


Fig. 5. Numerically calculated behaviour of the modulation depth M of the light reflected from the track as a function of the period Λ of the pit pattern for various deviations Δ from optimum focusing ($\Delta = 0$).

(31)

AS THE PIT-PIIT SPACING
DECREASES (ie f INCREASES)
THE PLAYBACK SIGNAL AMPLITUDE
MODULATION DIMINISHES

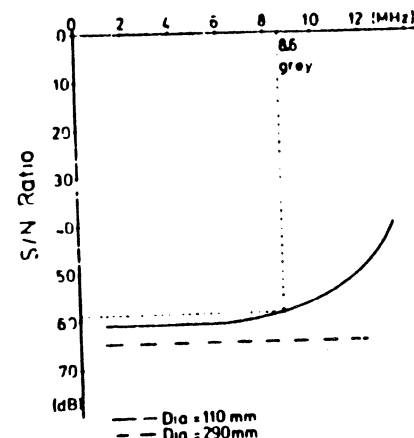
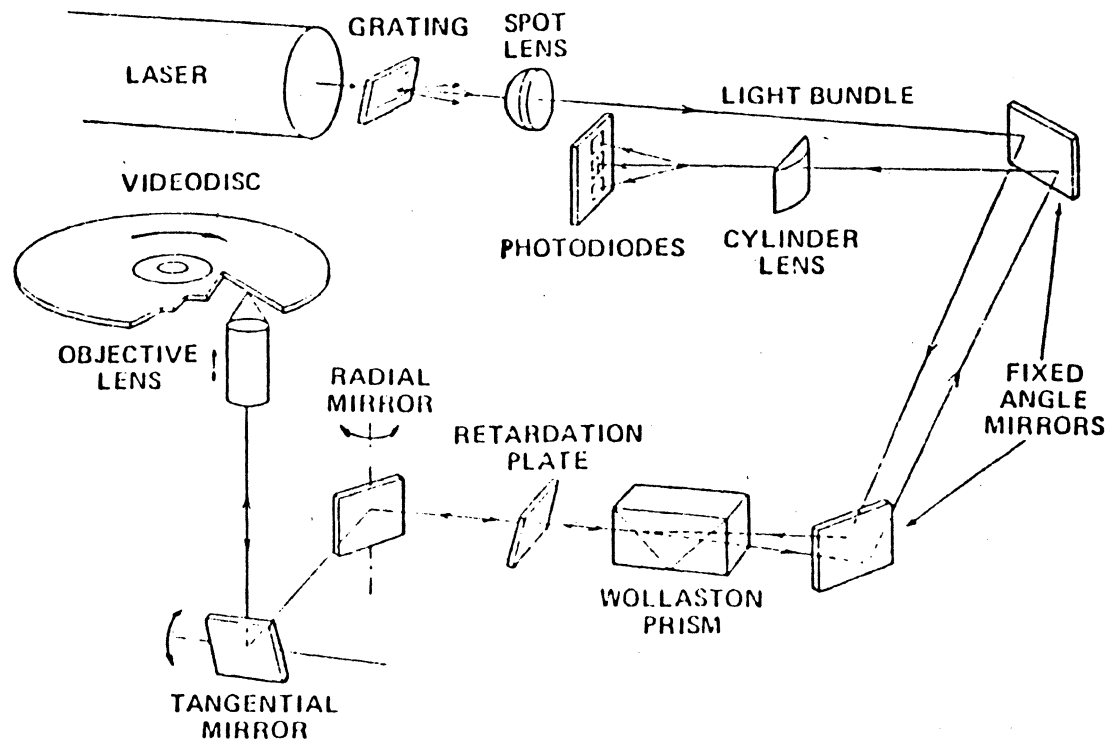


Fig. 13. SNR of complete system, with 30-KHz bandwidth and 0.40-NA lens.

(32)

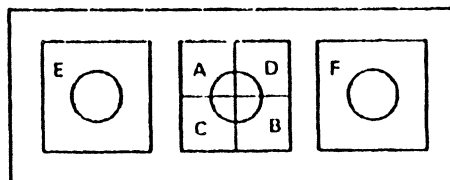
CONSUMER VIDEODISC SYSTEM

PLAYBACK ONLY

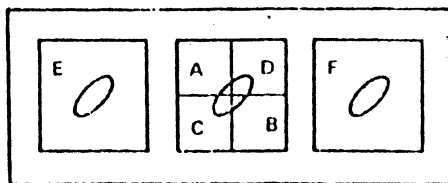


PHILIPS / MCA (25)

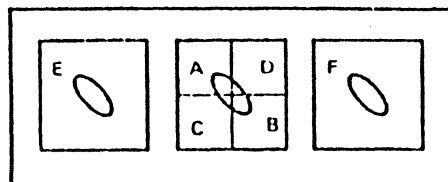
FOCUS ERROR DETECTION SCHEME FOR VIDEO DISK



DISC PERFECTLY FOCUSED



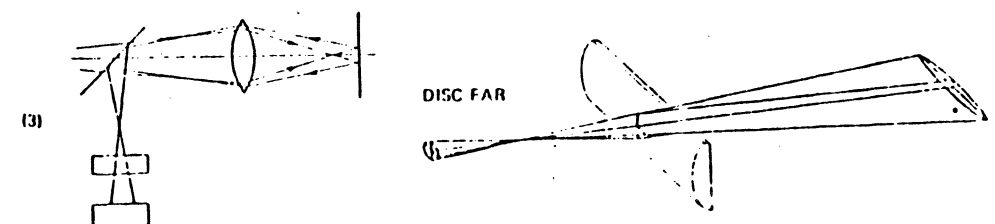
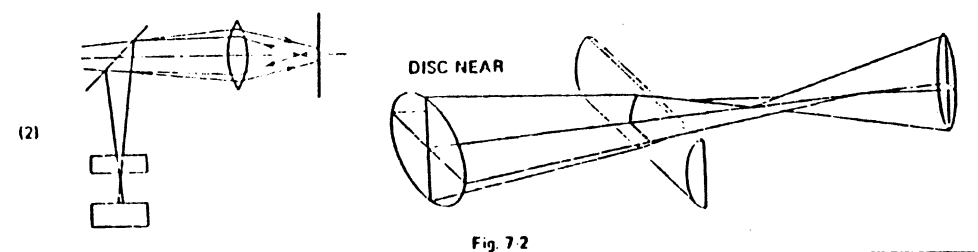
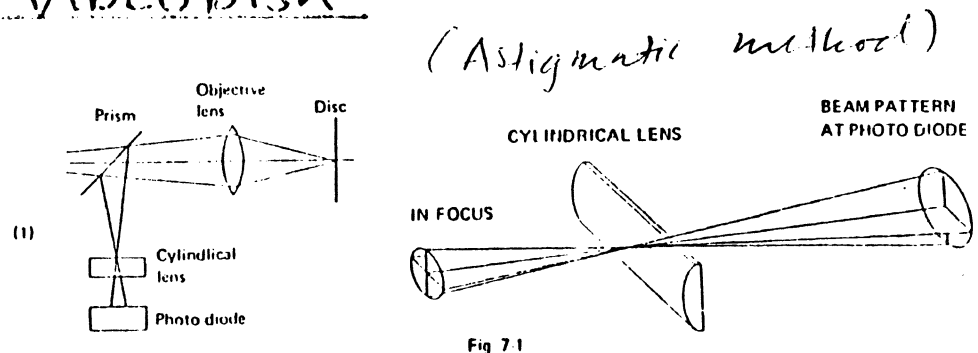
DISC TOO FAR



DISC TOO CLOSE

Figure 24 - Photodiode Arrangement and Focus Principle

CYLINDER LENS
(ASTIGMATIC METHOD)



Focus
error
signal

$$\propto (A+B) - (C+D)$$

(25)

TRACKING ERROR DETECTION SCHEME

VIDEODISC.

3. Tracking Servo Control

The 2 beams of both sides are arranged slightly out of alignment from each other as shown in Fig. 6. The corresponding reflected beams are applied to photo diodes A and C respectively (see Fig. 5). The tracking servo control maintains the difference between the 2 diode outputs at zero.

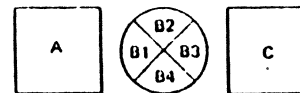


Fig. 5
Photo diode pattern

(Three-spot method)

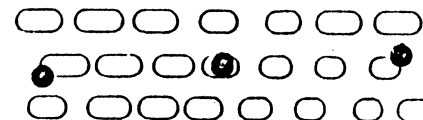
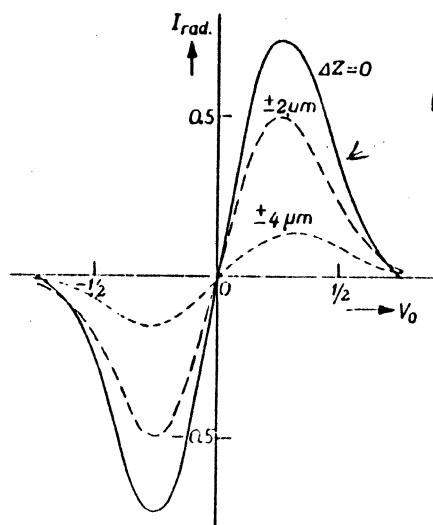


Fig. 6



loss of focus
affects tracking
ability

Fig. 6 The radial tracking signal as a function of the distance v_0 of the track from the origin for the focal settings $\Delta z = 0 \mu\text{m}, \pm 2 \mu\text{m}, \pm 4 \mu\text{m}$.

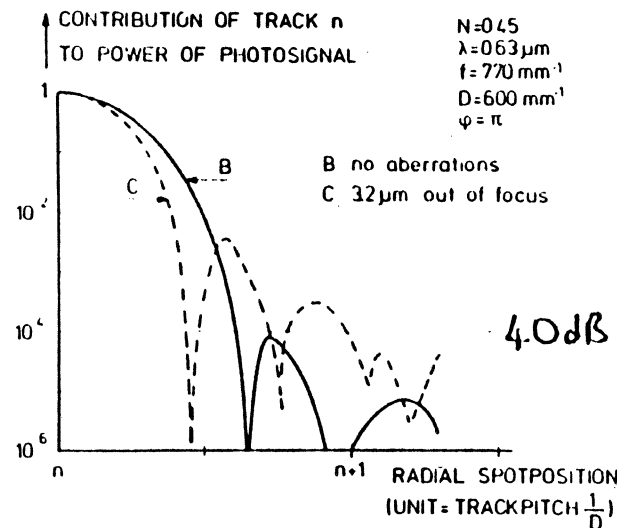
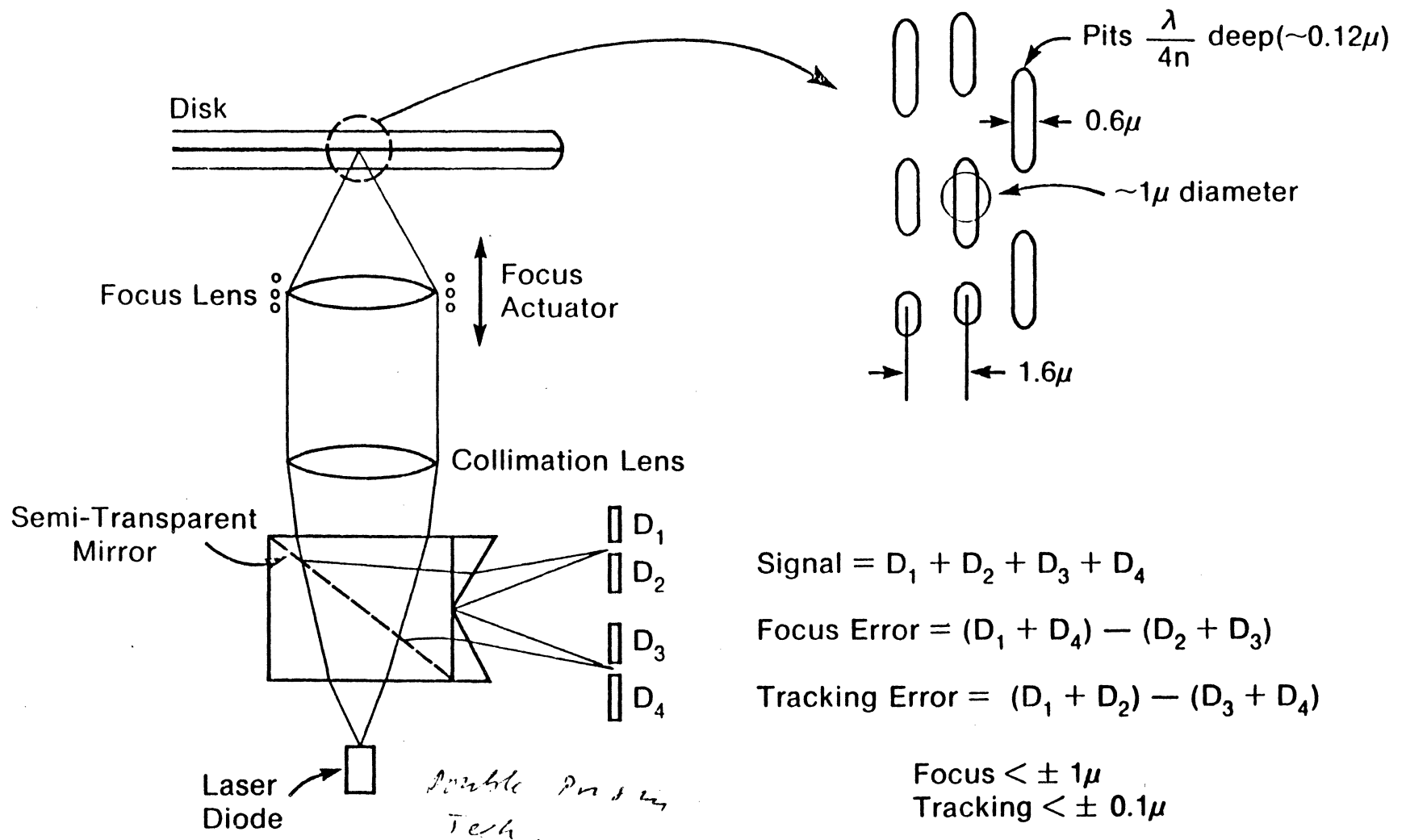


Fig. 4. Calculated contribution of a track to the signal power as a function of the radial spot position.

Track error

signal $\propto (V_A - V_C)$

Digital Audio Disc Read-Out



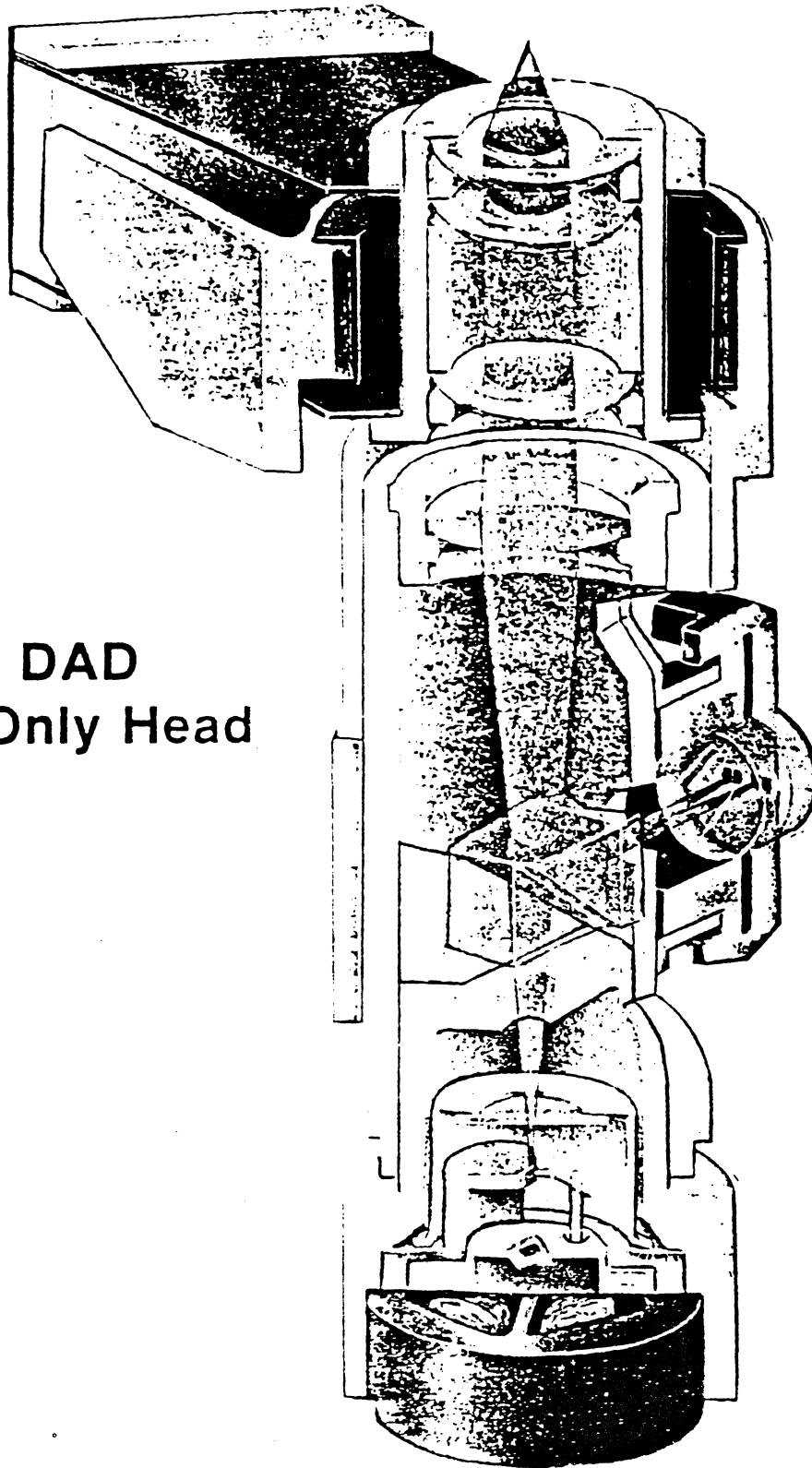
READ-ONLY OPTICAL DATA STORAGE

- DIGITAL AUDIO DISK (DAD, 1983)
 1. 120mm DIA. DISK - 1 HR. PLAY
 2. SONY/PHILIPS FORMAT STANDARDIZATION
 3. FIRST HIGH VOLUME PRODUCT FOR OPTICAL TECHNOLOGY
 4. SINGLE CHIP ECC - BER < 10^{-9}

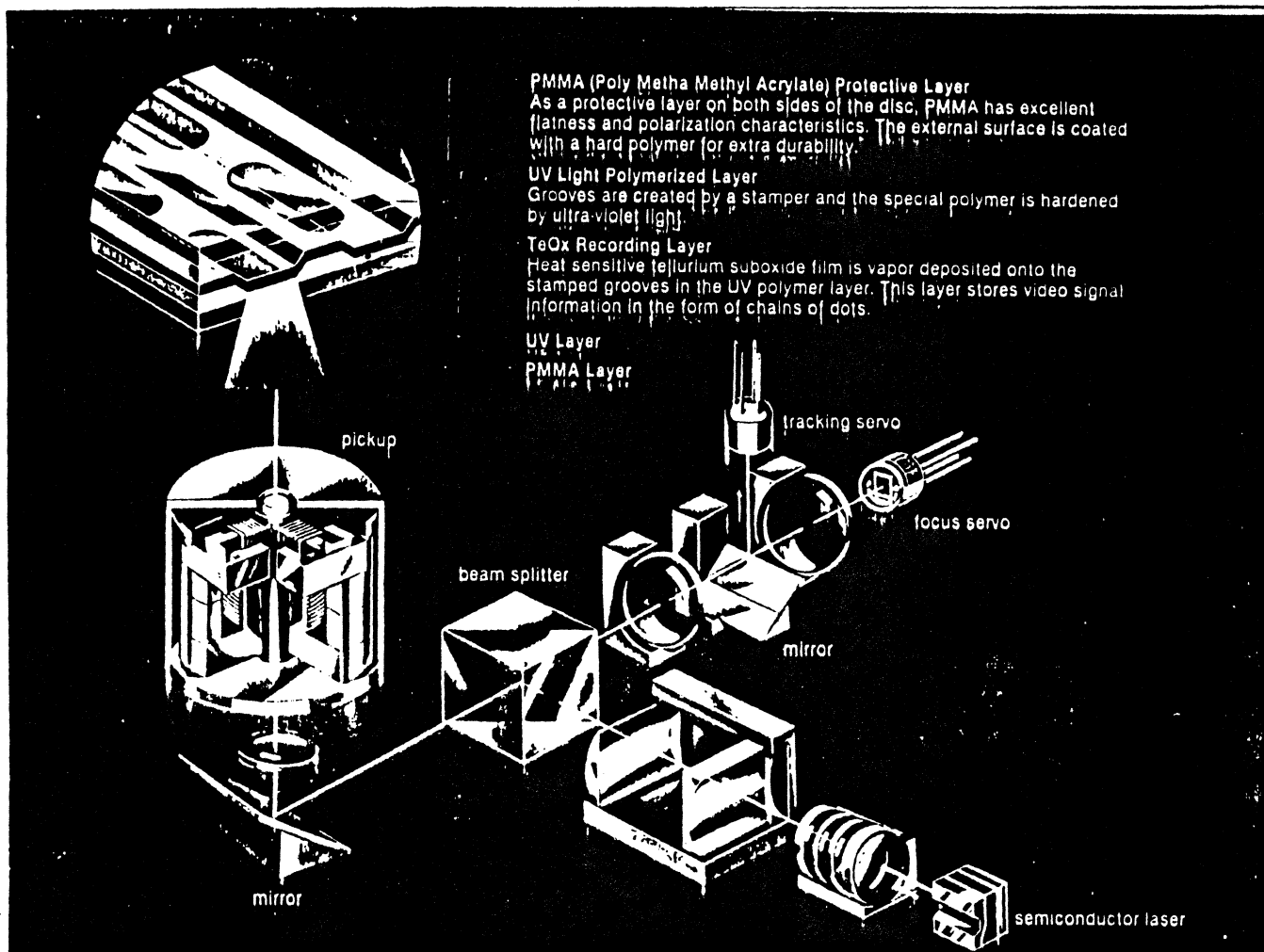
- DIGITAL DATA DISK (CD-ROM, 1984)
 1. BASED ON DAD TECHNOLOGY: 550 MB DISK CAPACITY
 2. SONY/PHILIPS FORMAT STANDARDIZATION
 3. INTRODUCTION 4Q84
 4. PLAYBACK UNIT PRICE: ~~\$400~~ \$1500
 5. ACCESS TIME < 3s, BER 10^{-12}
 - *6. EXTENDABLE TO LOW-END READ/WRITE SYSTEMS
 7. MEDIA SUPPLIERS: 3M, SONY, PHILIPS
 8. SONY WILL INSTALL AND LICENSE MEDIA FABRICATION EQUIPMENT

1-2" long.

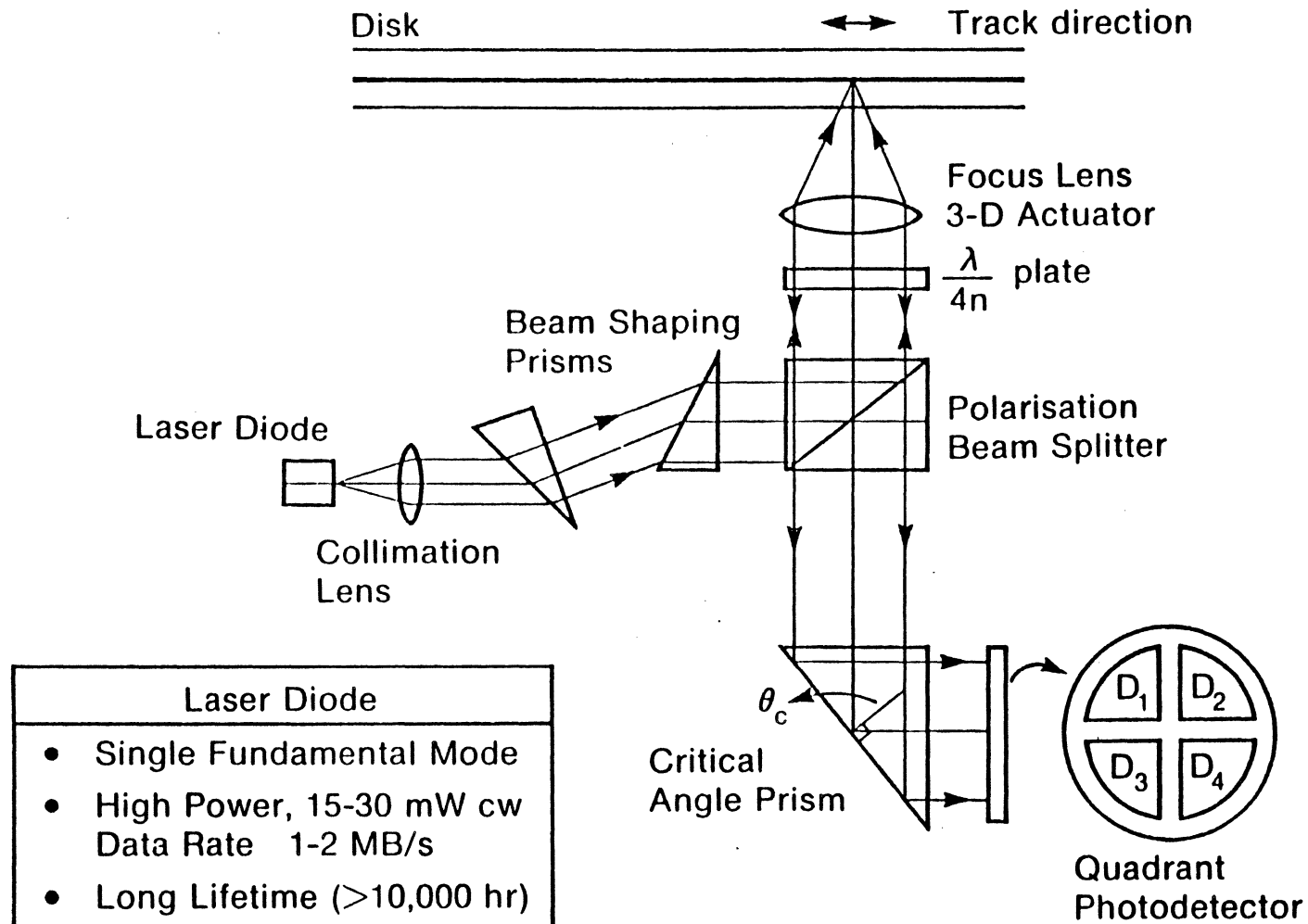
Philips DAD Read-Only Head



Optical Read/Write Head (Matsushita)



Diode Laser Read/Write Systems



Laser Diode
• Single Fundamental Mode • High Power, 15-30 mW cw • Data Rate 1-2 MB/s • Long Lifetime (>10,000 hr) • Future — Laser Arrays

$$\text{Data Signal} = D_1 + D_2 + D_3 + D_4$$

$$\text{Focus Error} = (D_1 + D_2) - (D_3 + D_4)$$

$$\text{Tracking Error} = (D_1 + D_3) - (D_2 + D_4)$$

WRITE-ONCE OPTICAL DATA STORAGE

- COMPUTER COMPATIBLE DATA STORAGE/RETRIEVAL: $\text{BER} < 10^{-10}$

1. HIGH PERFORMANCE

3MB/s DATA RATE

< 100ms AVG. ACCESS

2. MID-LOW PERFORMANCE

1.5 - 0.25 MB/s DATA RATE

150 - 450 ms AVG. ACCESS

- DOCUMENT STORAGE/RETRIEVAL SYSTEMS: $\text{BER} < 10^{-7}$

CURRENT WRITE-ONCE OPTICAL DATA STORAGE PRODUCTS

COMPANY	DISK CAP.*	DISK PRICE	DATA RATE	ACCESS TIME	SYSTEM PRICE
STC	4 GB	\$140	3MB/s	85 ms	\$130K
HITACHI	1.3 GB	\$300	0.44 MB/s	250 ms	\$1000/mo.
NEC/3M	1.3 GB	\$250	0.8 MB/s	450 ms	\$13,500
OPTIMEM	1 GB	\$100*	0.63 MB/s	150 ms	\$6000**

time

* Per Side

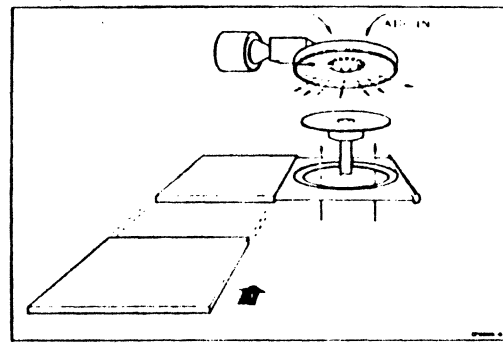
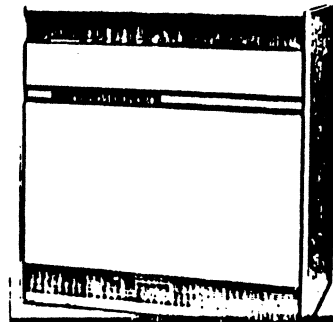
** OEM Quantity

*"2nd generation" w-o.
↓ 5 1/4" from factory
1.10 - 22 MB / side*

~1/2 - ~\$2K

*OEM
prod.*

STC 7640 Optical Storage Unit



PERFORMANCE CHARACTERISTICS

SEEK	
SINGLE TRACK	1.0 millisecond
AVERAGE TO ANY TRACK	61.9 milliseconds
AVERAGE ROTATIONAL LATENCY	22.8 milliseconds
AVERAGE TOTAL ACCESS TIME	84.7 milliseconds
MAXIMUM ACCESS TIME	140.6 milliseconds
MEDIA ACCESS	
LOAD/UNLOAD CYCLE TIME	12.0 seconds
(COMPLETE)	
TRANSFER RATE	
INSTANTANEOUS	3.0 Mbytes per second
BUFFERED	1.5 Mbytes per second

PHYSICAL CHARACTERISTICS

SIZE	
HEIGHT	55 in. (141.7 cm)
WIDTH	52 in. (132.0 cm)
DEPTH	32 in. (81.2 cm)

ENVIRONMENTAL CHARACTERISTICS

TEMPERATURE	
OPERATING	50 F to 90 F (15 C to 32 C)
NON-OPERATING	50 F to 101 F (10 C to 39 C)
HUMIDITY	
OPERATING	20% to 80% Non-Condensing
NON-OPERATING	5% to 95% Non-Condensing

STC 7440 Optical Media Unit

- 14" Aluminum platter with cartridge
- Projected Lifetime 10 yrs.
- ~ 600 Mb/in²

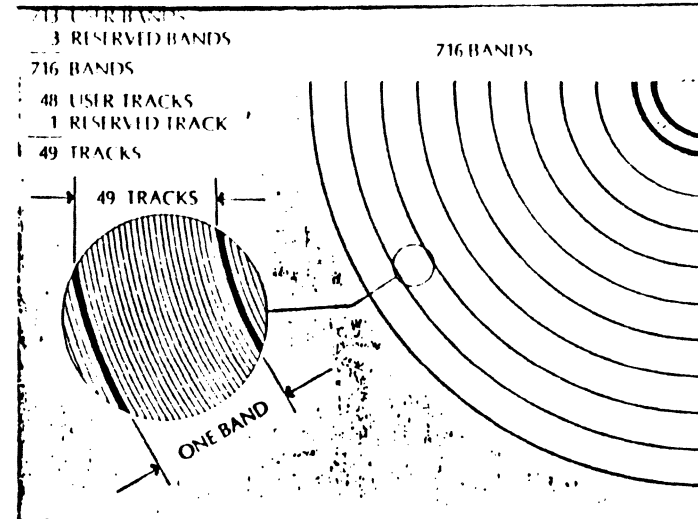


TECHNOLOGICAL CHARACTERISTICS

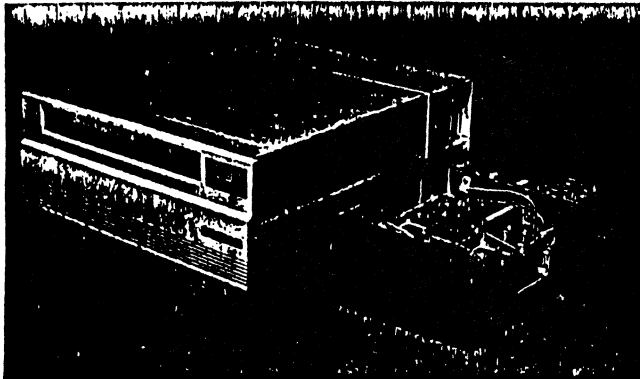
CAPACITY	
Formatted	4.0 Gigabytes
BAND CAPACITY	
Formatted	5.7 Megabytes
TRACK CAPACITY	
Formatted	118.5 Kilobytes
BIT ERROR RATE	
Raw	1 in 10 ⁵
Corrected	1 in 10 ¹¹

ENVIRONMENTAL CHARACTERISTICS

TEMPERATURE	
Operating	59° to 90°F (15°C to 32°C)
Shipping	-40°F to 140°F (-40°C to 60°C)
HUMIDITY	
Operating	20% to 80% Non-Condensing
Shipping	5% to 99% Non-Condensing



**Optimem (Xerox/T-CSF) Write-once Optical
Storage System (FSC 1H84)**



Shugart Corp's Optimem 1000 laser-based optical disk drive is shown with an
SA801 5.25" floppy for size comparison.

SCSI/SASI Interface
1200 rpm

Media

- Type PMMA Air Sandwich
- Active Layer Au-based Alloy
Bubble-Mode
- Projected Life > 10 yrs.
- BER (corrected) 10^{-12}
- Format
 - Linear Density 15 KbPI
 - Track Density 15 KTPI
 - Areal Density 225 MbPI²

5.25" floppy drive

DOCUMENT STORAGE/RETRIEVAL SYSTEMS

1. VIEWED BY MANY JAPANESE COMPANIES AS AN ENTRY PRODUCT TO OPTICAL STORAGE
2. 5-10 JAPANESE COMPANIES HAVE ANNOUNCED OR SHIPPED
3. STAND-ALONE SYSTEMS INCLUDE:
 - HARD COPY INPUT/OUTPUT (~ 10s)
 - HIGH RES. CRT
 - STORAGE UNIT (~ 0.5s ACCESS)
 - PROCESSOR
4. TYPICALLY \$40-80K
5. 12" DISK CAPACITY 10,000-20,000 A4 DOCUMENTS
6. TOSHIBA 'TOSFILE' (FCS 1Q82) REPORTED TO BE INSTALLED AT 200-500 LOCATIONS

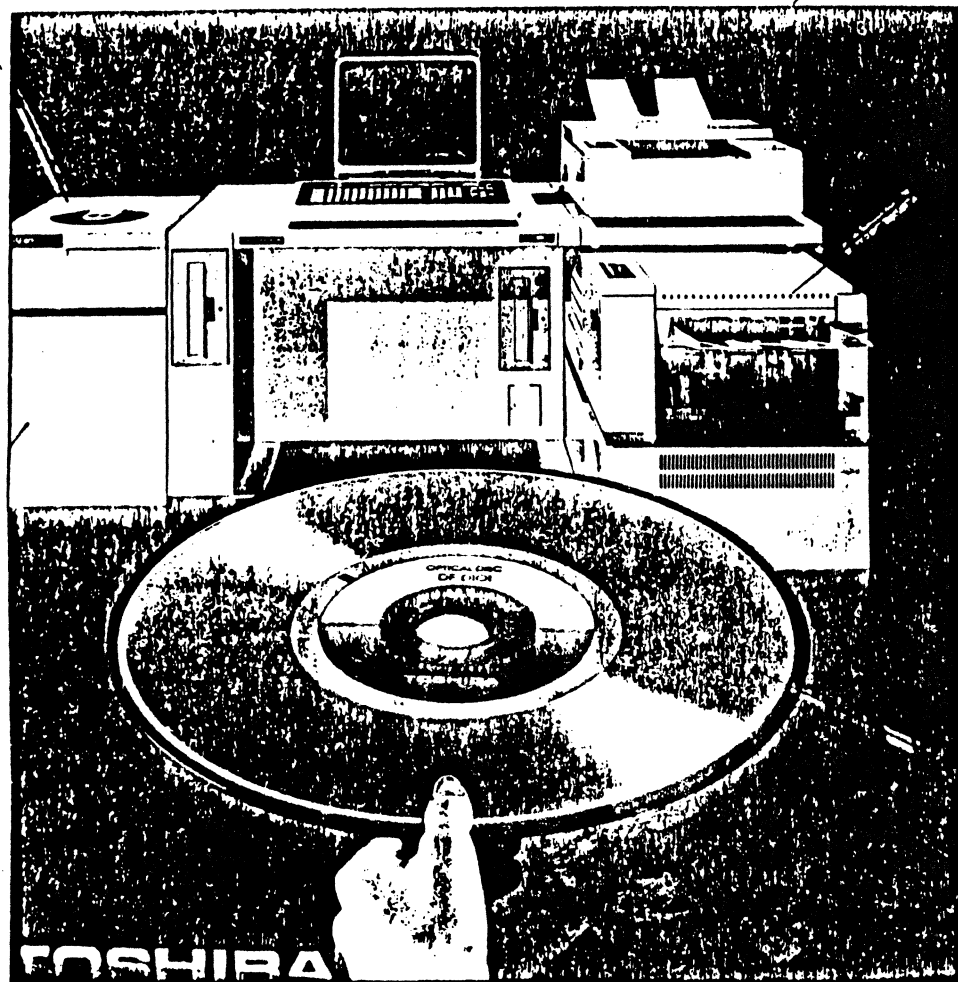
Document/Image Storage System

Optical Storage
Unit

Optical Document
Scanner

Printer

Processor



Toshiba DF-2100	
Capacity (per disk)	10,000 A4 Documents @ 8 lpmm horiz. 7.7 lpmm vert.
Input/Output Response	~ 10 s (hard copy)
BER	~ 10^{-8}

30 cm dia. Disk
Double Sided
36,000 Tracks/Side
1.2 GB/Side

IDEAL ERROR SENSING

TRANSDUCER

① PASSES THROUGH ORIGIN
- NO DC OFFSETS

② WIDE RANGE OF LINEAR
RESPONSE

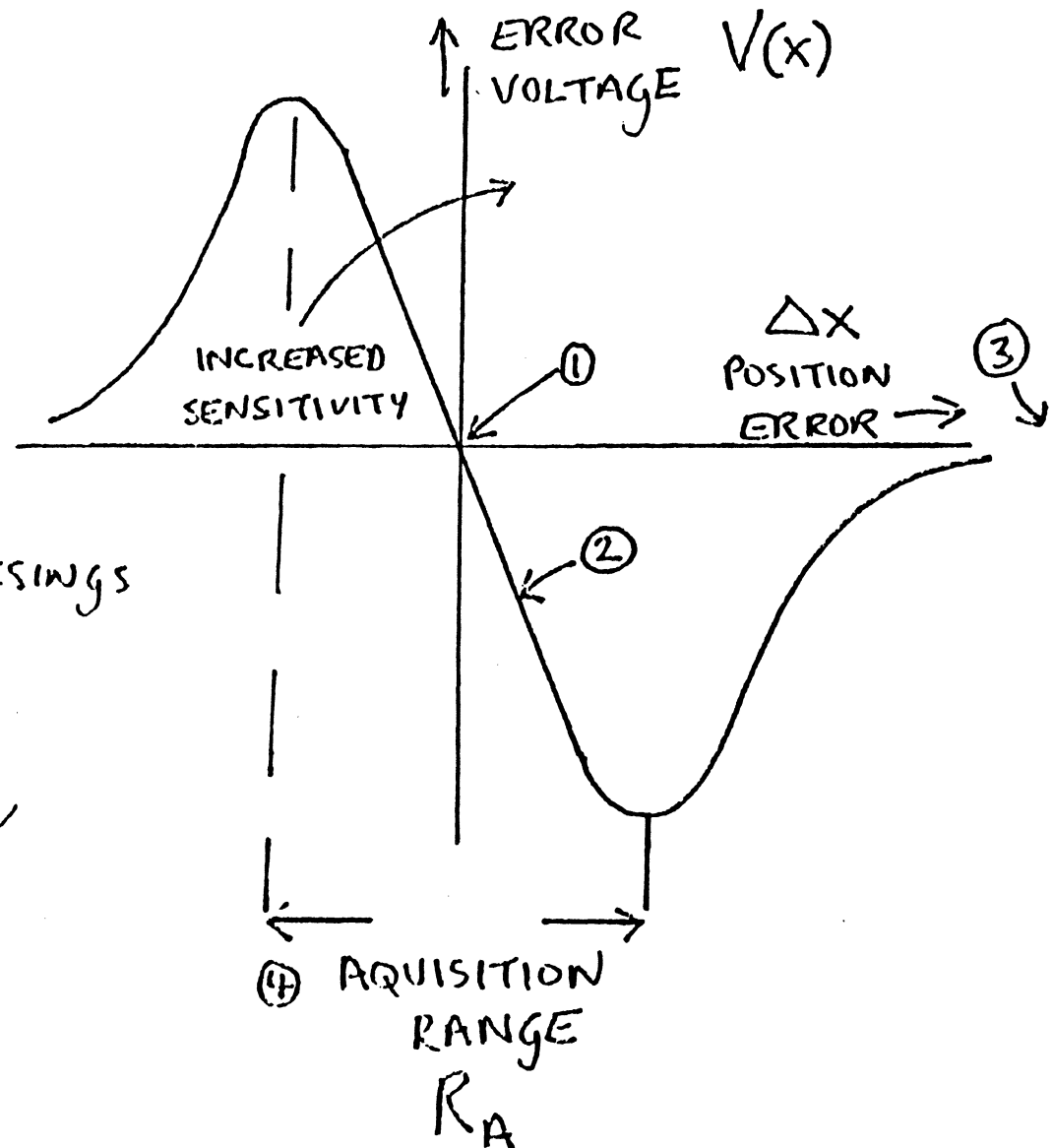
SENSITIVITY $\frac{dV}{dx}$ GOOD

③ NO SECONDARY ZERO CROSSINGS

④ WIDE ACQUISITION RANGE

NOTE $\left(\frac{dV}{dx}\right)_{x=0} \uparrow, R_A \downarrow$

IN GENERAL



SERVO-PERFORMANCE —

DISK GEOMETRY SPEC., TRADEOFFS

FOCUS/FLATNESS

RESIDUAL FOCUS ERROR DEPENDS ON

- 1) DISK FLATNESS
- 2) ROTATIONAL VELOCITY
- 3) SERVO PERFORMANCE

(a) Determine max. permissible focus error, ϵ
eg $\epsilon \approx 1.5 \mu$ consumer video disc, NA 0.4
Playback only

$\epsilon \approx 0.2 \mu$ read/write disk NA ≥ 0.5

Depends on NA of lens (depth of focus)
+ read only or read/write, (write more critical)

DISK-SERVO TRADEOFFS (cont'd)

b) MEASURE DISK RUN-OUT SPECTRUM AT SYSTEM RPM

$$\Delta z = \sum_{n=0}^{\infty} A(n\omega_0) \sin(n\omega_0 t + \phi_n)$$

(c) CHECK IF OPEN LOOP SERVO GAIN CAN REDUCE EACH $A(\omega_n)$ BELOW ϵ , MORE SPECIFICALLY

$$\frac{A(\omega_n)}{G(\omega_n)} < \epsilon \quad \text{and} \quad \sum_{n=0}^{\infty} \frac{A(\omega_n)}{G(\omega_n)} < \epsilon$$

(d) IF NOT, IMPROVE DISK FLATNESS OR

IMPROVE SERVO GAIN OR

REDUCE RPM OR

REDUCE NA (INCREASE D.O.F. + SPOT SIZE
ie REDUCE DATA DENSITY)

10 rps DISK SPEED

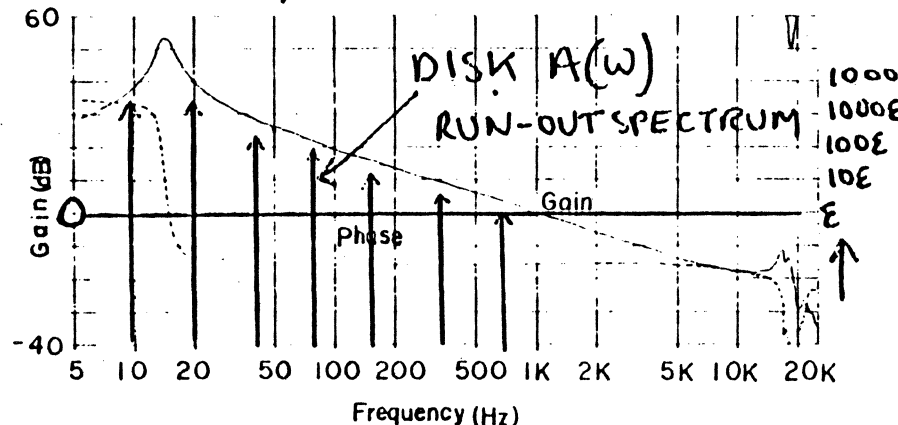


Fig. 1 Transfer characteristics of the vertical direction

HOW FLAT IS FLAT ENOUGH

ALL disk $A(\omega) < \text{Gain curve}$

SYSTEM ACCEPTABLE

AT 10 rps

PROVIDED $\sum_{\omega} A(\omega) < E$

(41)

40 rps DISK SPEED

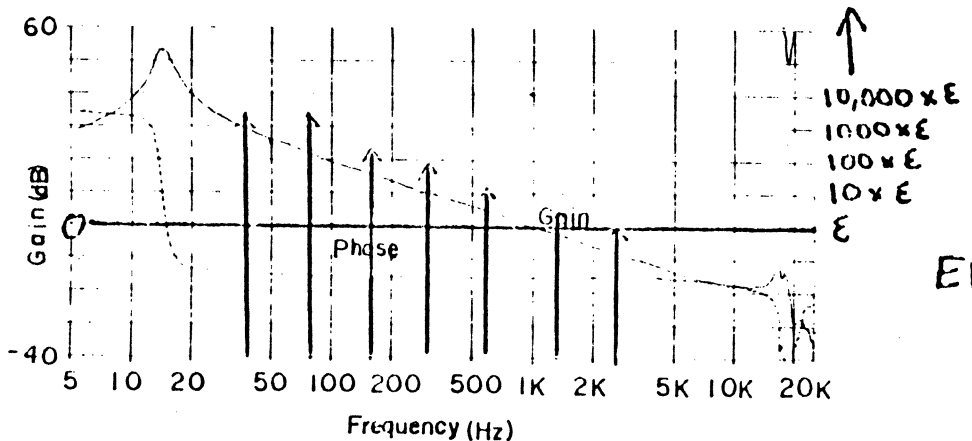


Fig. 1 Transfer characteristics of the vertical direction (41)

DISK
VERTICAL
RUNOUT

ALL disk $A(\omega) > \text{Gain curve}$

$\Rightarrow \text{FOCUS ERROR} > E$

EITHER:- DISK IS NOT FLAT ENOUGH

$\Rightarrow \text{MEDIA IMPROVEMENT}$

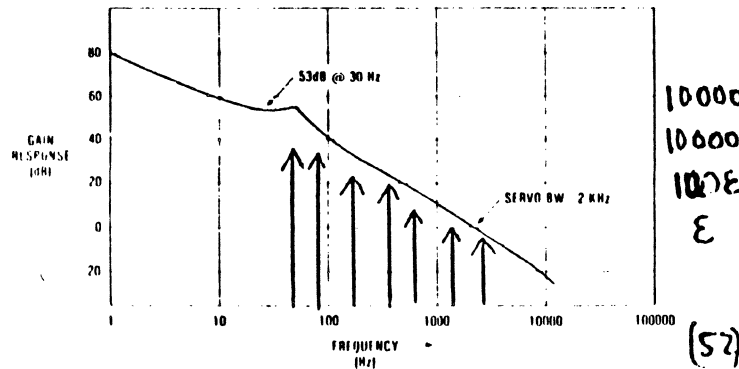
SERVO TOO LOW PERF.

$\Rightarrow \text{SYSTEM IMPROVEMENT}$

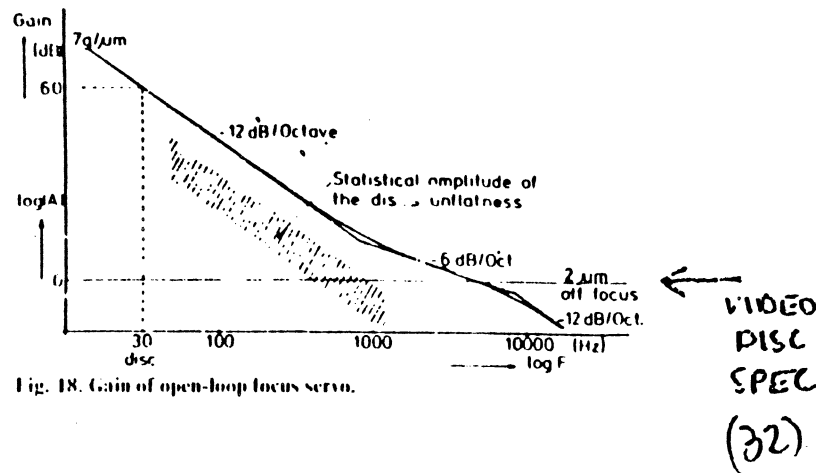
DISK-SERVO TRADEOFFS

40 rps

↑
VERTICAL
RUNOUT



SAME DISK, BETTER (ie HIGHER
PERFORMANCE) SERVO, SYSTEM
NOW ACCEPTABLE
— ALSO COSTS MORE!



NOT ALL DISKS ARE THE
SAME, MUST ACCOUNT
FOR DISK STATISTICS TO
OBTAIN A REASONABLE
YIELD.

HOW ROUND IS ROUND ENOUGH?

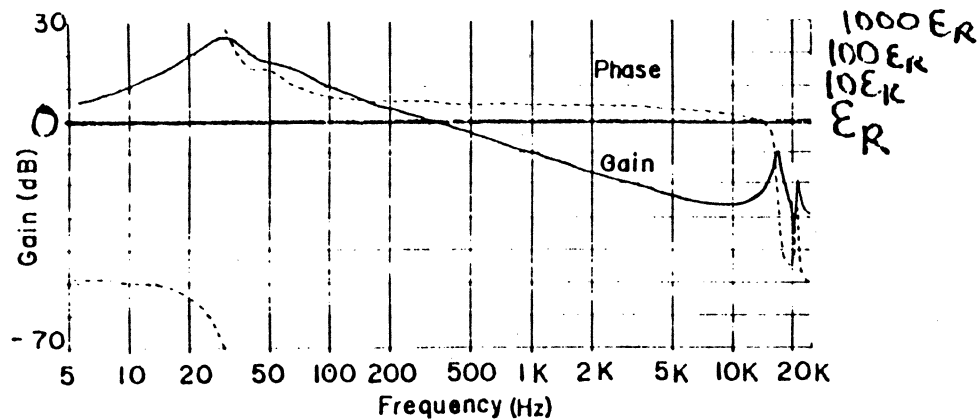


Fig. 7 Transfer characteristics of the radial direction

(41)

SAME METHODOLOGY PERMITS
DISK ROUNDNESS — TRACKING
SERVO PERFORMANCE TRADEOFF

E_R = MAX PERMISSIBLE
OFF-TRACK ERROR

DEPENDS ON

- 1) NA
 - 2) PITCH
 - 3) CROSSTALK REQMT.
- DIGITAL ≤ 30 dB
VIDEO ≤ 50 dB

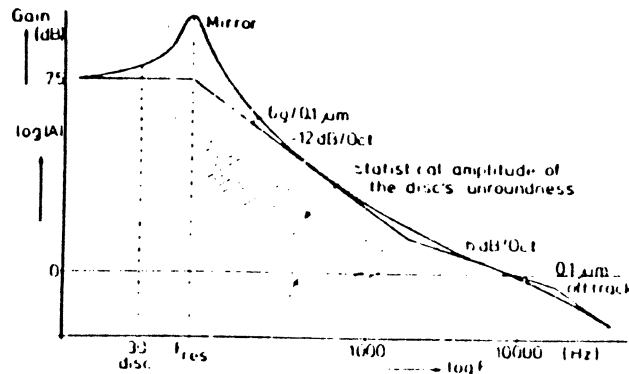


Fig. 19. Gain of open-loop radial tracking servo.

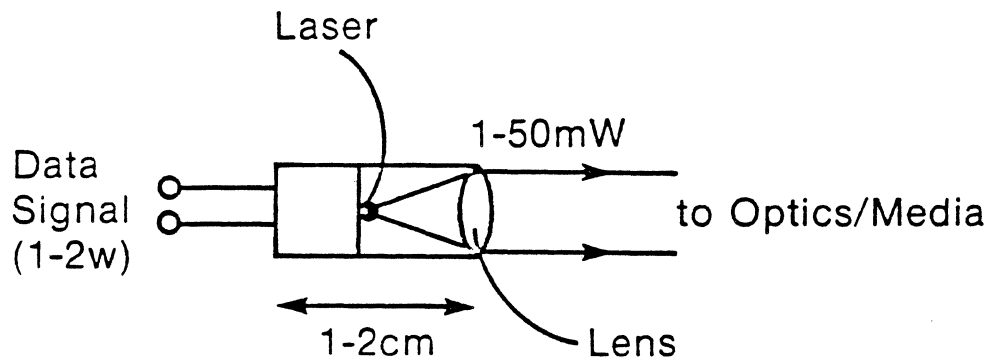
AGAIN — STATISTICS MUST
BE ACCOUNTED FOR

← VIDEODISC SPEC.

(32)

Semiconductor Diode Lasers

GaAlAs: $\lambda = 780\text{-}850\text{nm}$



- Compact - permits modular R/W head design
- Limited power, very efficient
- Directly modulatable
- Lifetime $\geq 10,000$ hr
- Less expensive
- Data rates 1-3 MB/s
- Integrated arrays for very high data rates

DIODE LASER BASICS

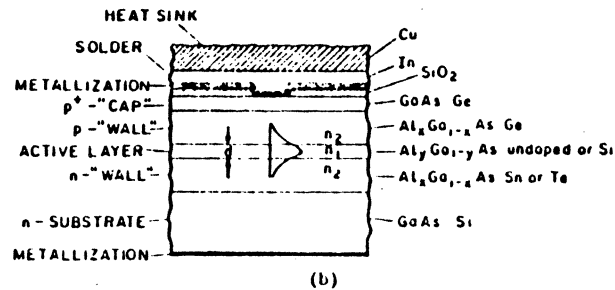
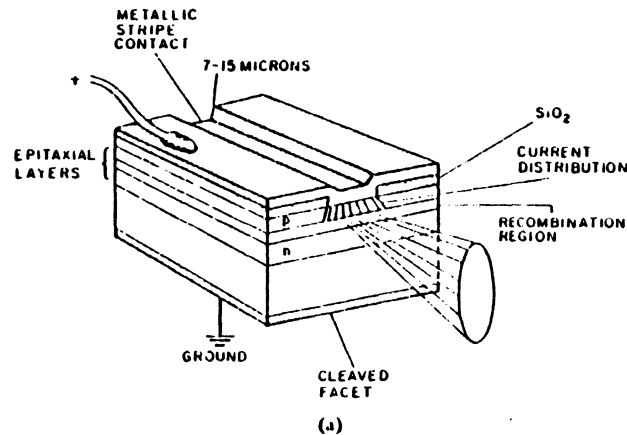


Fig. 13. (a) Schematic representation of the stripe geometry laser structure (after Kressel and Butler [7]). (b) Schematic cross-section of the standard oxide-stripe AlGaAs diode laser for CW room temperature operation. The active layer of thickness d ($0.05-0.2 \mu\text{m}$) is placed $2-3 \mu\text{m}$ away from the contact stripe. The $\text{Al}_x\text{Ga}_{1-x}\text{As}$ ($x = 0.3-0.4$) "wall" layers have a refractive index n_2 lower than the index n_1 of the $\text{Al}_y\text{Ga}_{1-y}\text{As}$ ($y = 0.05-0.1$) active layer (i.e., $\Delta n = n_1 - n_2 = 0.2-0.3$).

LASER OSCILLATES (EMITS) ONLY IN PERMITTED MODES, DEFINED BY THE GEOMETRIC, OPTICAL AND ELECTRIC PROPERTIES OF THE ACTIVE REGION

1) TRANSVERSE SPATIAL MODES
($\perp$ TO JUNCTION PLANE)

2) LATERAL SPATIAL MODES
($\parallel$ TO JUNCTION PLANE)

3) LONGITUDINAL SPECTRAL MODES

REQUIREMENTS ON DIODE LASER SOURCES

FOR OPTICAL DATA READ/WRITE

APPLICATIONS

- 1) SINGLE FUNDAMENTAL SPATIAL MODES FOR BOTH TRANSVERSE AND LATERAL DIRECTIONS
 - TO ACHIEVE DIFFRACTION LIMITED SPOT DIAMETER WITH HIGH OPTICAL EFFICIENCY FOR THE READ/WRITE OPTICAL SYSTEM
 - TO PERMIT DESIGN OF A SINGLE OPTICAL SYSTEM FOR BATCH MANUFACTURED LASERS (INDIVIDUAL LASER PROPERTIES ARE CLOSER IF ALL ARE FUNDAMENTAL MODE.)

DIODE LASER REQUIREMENTS (CONT'D)

- 2.) PREFER MULTI-MODE SPECTRAL OPERATION TO MINIMISE EFFECT OF FEEDBACK (UNLESS INTEND TO USE SCOOP EFFECT)

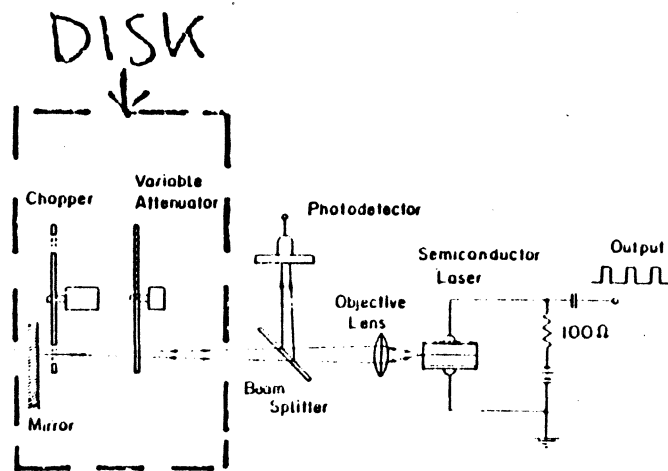


Fig. 11. Experimental setup used in the SCOOP system.⁷

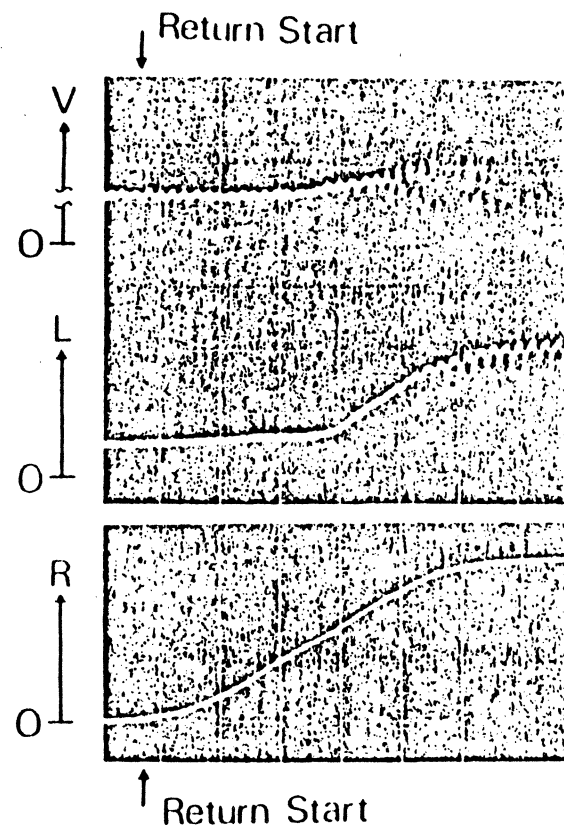


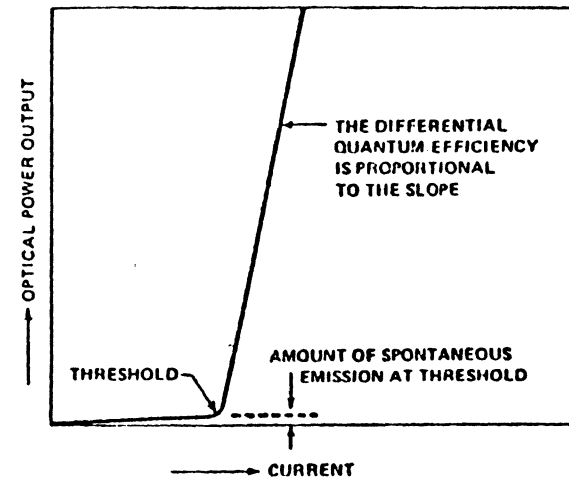
Fig. 10. Transient responses of the voltage V across the laser electrodes and the laser output L to the turnon of the return beam R .⁷
Vertical scale: 5 mV/div. Horizontal scale: 0.2 μ sec/div.

DIODE LASER REQUIREMENTS (CONT'D)

3) LOW THRESHOLD, HIGH DIFFERENTIAL QUANTUM EFFICIENCY
— TO MINIMISE POWER REQUIREMENT

4) LOW SPONTANEOUS
EMISSION AT THRESHOLD
TO PERMIT MAXIMUM
RATIO BETWEEN OUTPUT
POWERS WHEN LASING
UNDER WRITE OR READ
POWER LEVEL CONDITIONS

Figure 4.
LIGHT OUTPUT
CHARACTERISTICS



5) BEAM CHARACTERISTICS (ESPECIALLY BEAM POINTING
DIRECTION) UNCHANGED AT
READ ($\sim 1-3\text{mw}$) AND WRITE ($15-30\text{mw}$) POWER LEVELS

DIODE LASER REQUIREMENTS (CONT'D)

- 6) CHARACTERISTICS NOT STRONGLY TEMPERATURE
DEPENDENT
- 7) CAPABLE OF SINGLE SPATIAL MODE OUTPUT TO
RELATIVELY HIGH POWERS (15-30mw)
- 8) ALL THIS — AND LONG LIFETIME
~ 10,000 hrs
AT WRITE LEVELS

DESIGN STRATEGY FOR HIGH POWER, LONG-LIVED SINGLE MODE DIODE LASERS

1) HIGH POWER - LONG LIFE:

- (a) LOW POWER THRESHOLD AND HIGH DIFF. QUANT. EFFICIENCY HELP TO REDUCE HEAT LOAD INTO THE DEVICE ACTIVE REGIONS .
- (b) MINIMISE LIGHT POWER DENSITY AT FACETS
 - LARGE OPTICAL CAVITY (LOC) STRUCTURES
 - NON-ABSORBING FACET CONSTRUCTION
- (c) PASSIVATE FACETS
 - DIELECTRIC QUARTER-WAVE STACKS DEPOSITED ON FACETS
- (d) DESIGN A GOOD DRIVER WITH NO TRANSIENTS !

DESIGN STRATEGY (CONT'D)

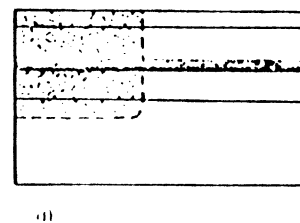
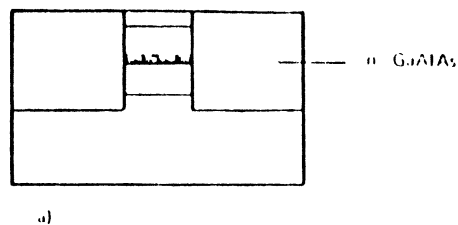
2) SINGLE SPATIAL MODE OPERATION

- TRANSVERSE RELATIVELY EASY

- LATERAL INTRODUCTION OF SOME NON-PLANAR GEOMETRY OR REFRACTIVE INDEX VARIATIONS TO PROVIDE OPTICAL CONFINEMENT IN ADDITION TO ELECTRICAL CONFINEMENT PROVIDED BY THE STRIPE CONTACT.

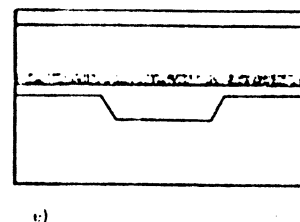
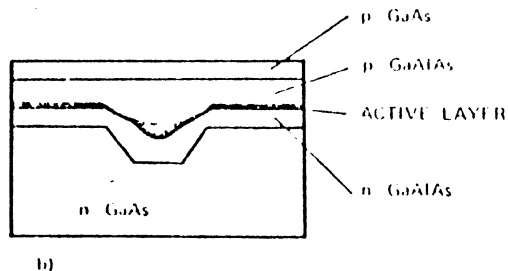
DESIGNS PROVIDING LATERAL OPTICAL MODE CONFINEMENT

* BH, BH-LOC
(HITACHI, CALTECH)



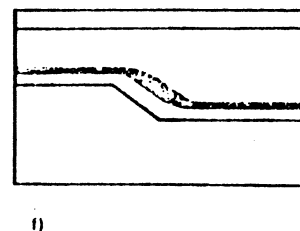
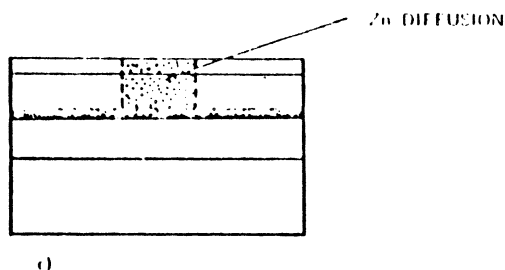
TJS
(MITSUBISHI) *

* CDH, CDH-LOC
(RCA)



CSP TYPE
(HITACHI, SHARP)

Zn DEEP-DIFFUSION
(NEC)



TERRACE SUBSTRATE
(MATSUSHITA)

* DETAILS
BELOW

Figure 4 Schematic Structures of some Laterally Index Confined Lasers (adapted from ref. 49)

- a = Buried Heterostructure (ref. 50)
- b = embedded structure (refs. 51, 52)
- c = deep diffusion stripe (ref. 53)
- d = Transverse Junction Stripe (ref. 54)
- e = Channeled-Substrate Planar (ref. 55)
- f = Terraced Substrate (ref. 56)

a, c, d $\tilde{n}$ VARIES Laterally
b, e, f $\tilde{n}_{eff}$ VARIES Laterally

OPTICAL STORAGE MEDIA

- **Preformatted Substrate Technology is the Key Common Factor**
- **Read-Only Disk Fabrication Technology Provides the Basis For Read/Write Disk Substrate Technology**

DISK SUBSTRATES

*allow
use in the
good*

a) Glass:	Good surface quality Dimensionally stable Chemically stable	Very expensive Bulky Fragile
b) Aluminum:	Currently mass-produced Dimensionally stable Chemically stable	Moderately expensive Need surfacing layer Reflective-mode disk structures only
c) Polymer:	Mass production underway for consumer video disc formattable lowest cost and bulk	Careful design and pro- cess control needed to achieve good surface quality, mechanical and chemical stability

*can be chemically
strengthened*

POLYMER SUBSTRATES FOR OPTICAL STORAGE

200mm
40

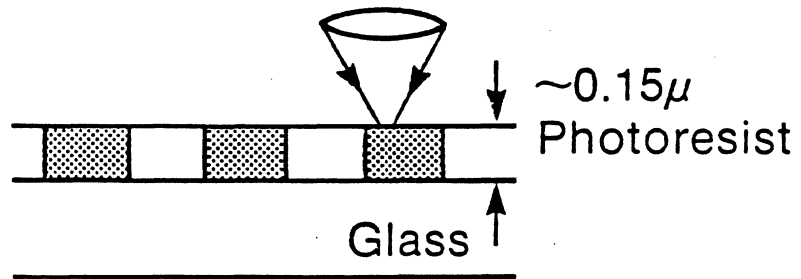
200mm
40

Property	PMMA	PVC	PC
Birefringence	Acceptable	Marginal	Problematic
Absorption ($\lambda = 633\text{nm}$)	~ 5%	~ 15%	~ 5%
Dimensional Stability	Moisture Sensitive	Temperature Sensitive	Good
Glass Temperature	~ 110°C	~ 70°C	~ 140°C
Process	Injection Molding	Injection Molding	Injection Molding
Cost	Moderate	Low	High
Application	Videodisc	CED Videodisc	DAD

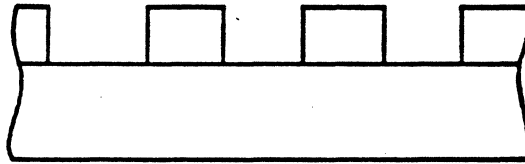
Read-Only Disc Fabrication

1. Mastering process

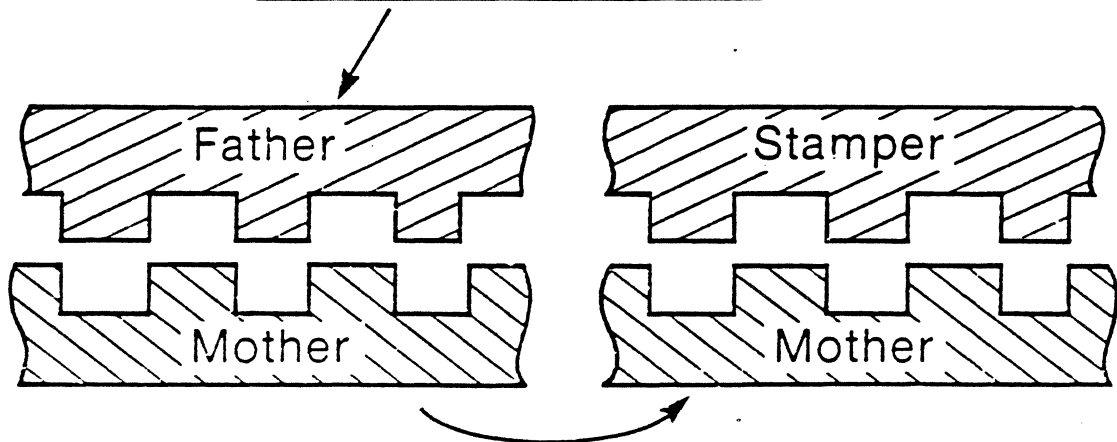
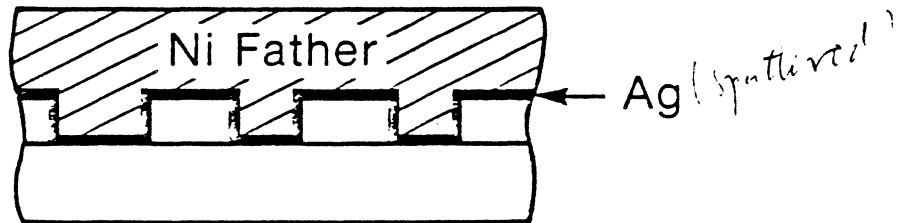
- Exposure



- Development



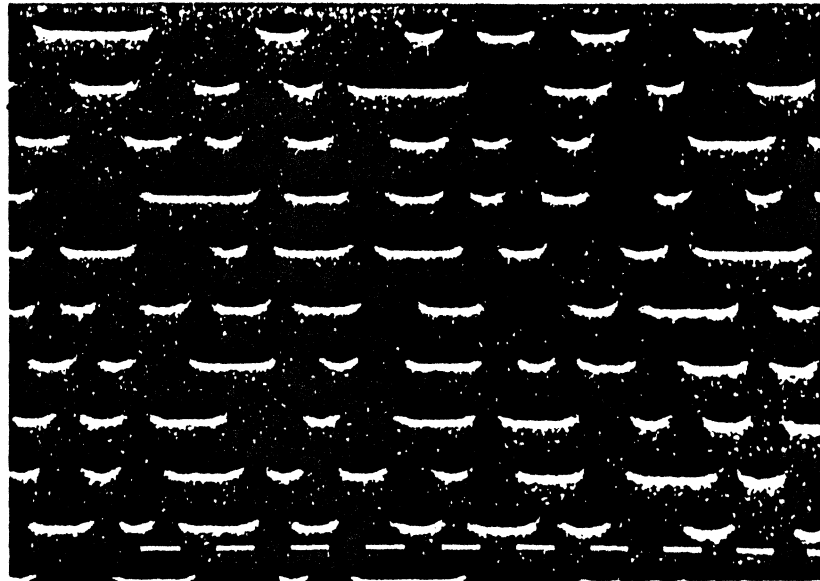
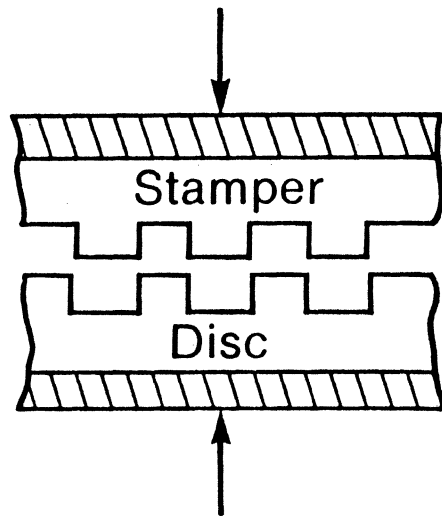
- Plating



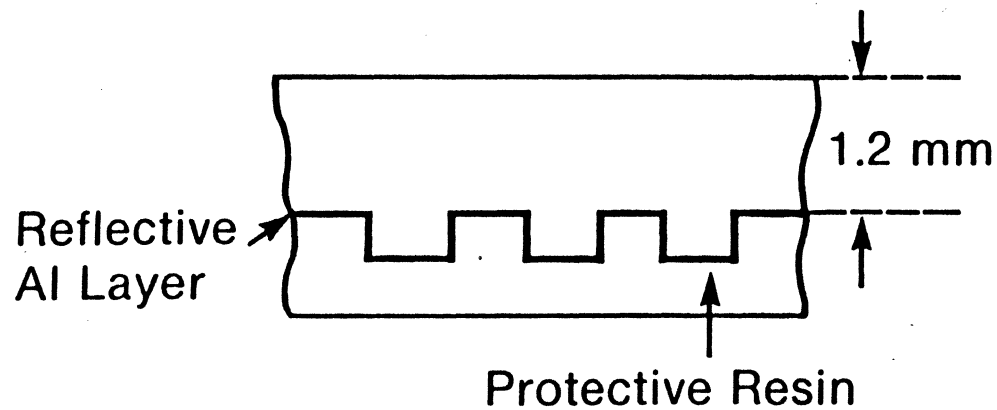
Read-Only Disc Fabrication

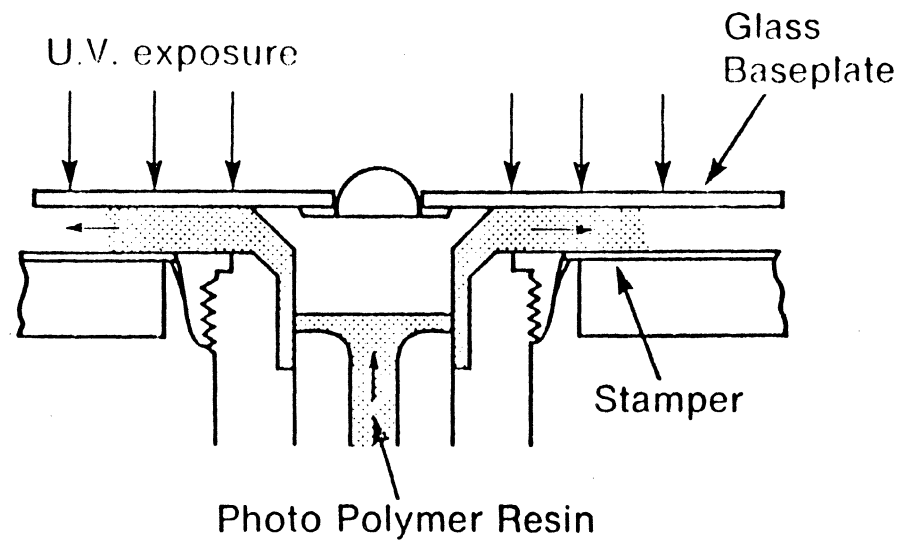
2. Replication and Finishing

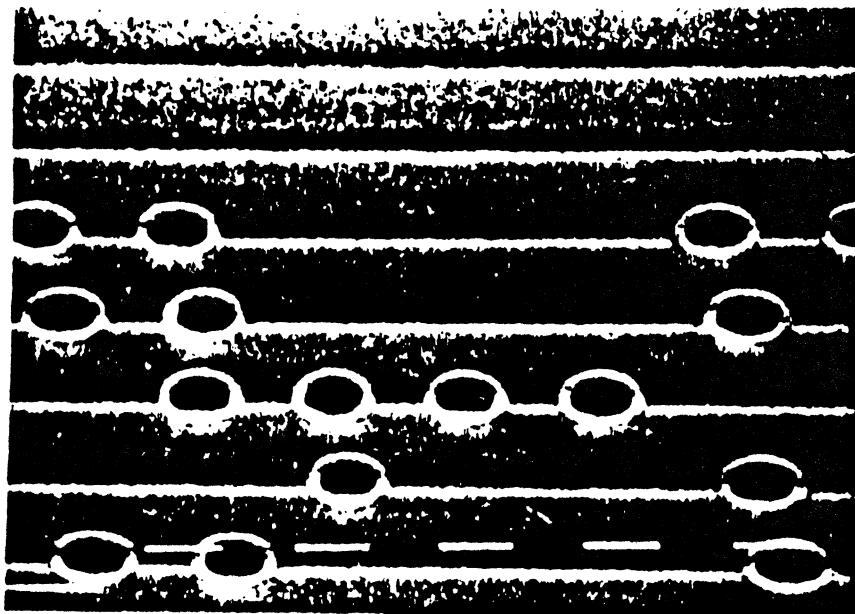
- Injection Molding



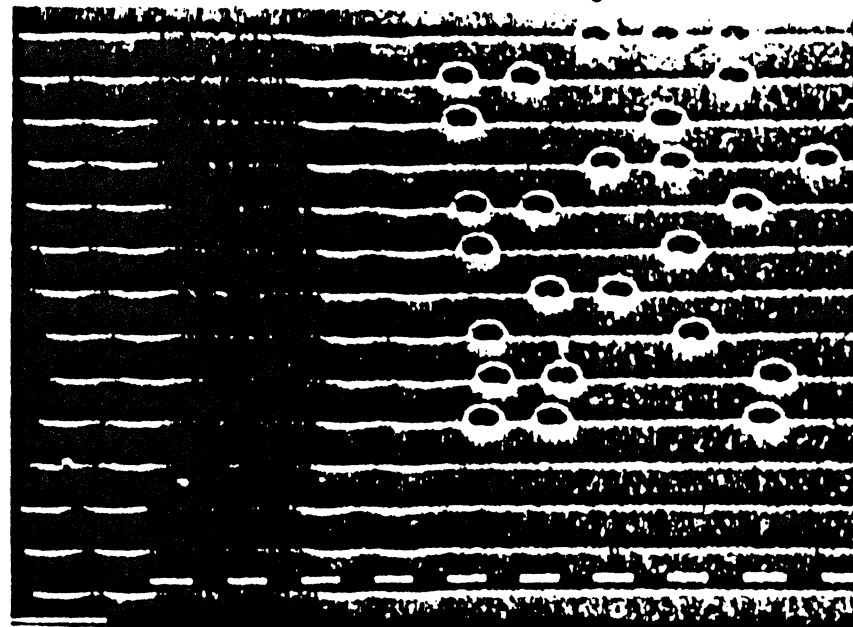
- Finishing







[3] Scanning electron microscope photo shows pre-recorded heading structure and recorded data in the groove.



PHILIPS PREGROOVE DISC

K. BULTHUIS et al IEEE SPECTRUM AUG(79)

ALAN E. BELL
IBM

NUMERICAL APERTURE / ENCAPSULATION THICKNESS TOLERANCE TRADE-OFF

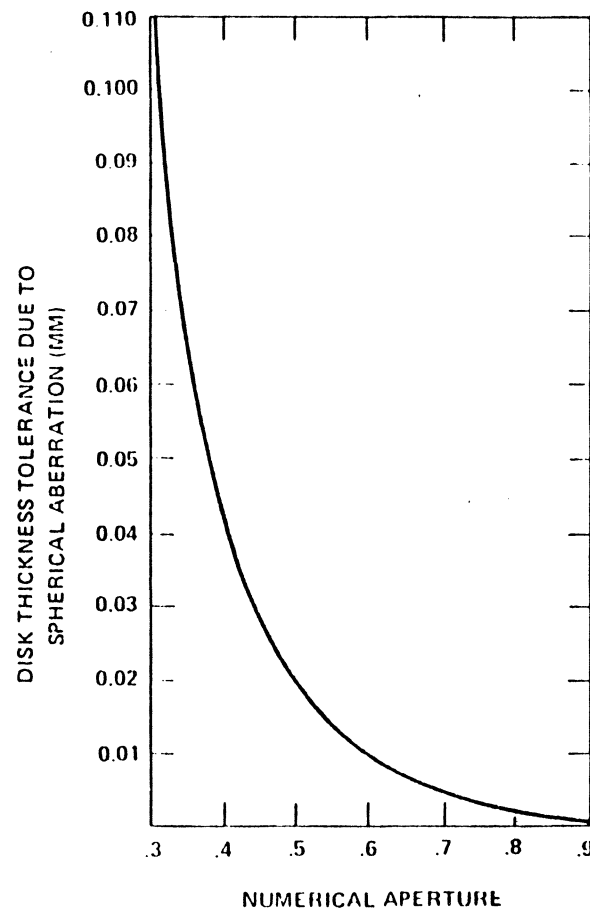


FIG. 1 NUMERICAL APERTURE VERSUS
ALLOWABLE DISK THICKNESS TOLERANCE

(24)

TOLERANCE TO
OVERCOAT/DISK THICKNESS
VARIATIONS

$$\sim \frac{1}{(NA)^3}$$

⇒ HIGH NA (≥ 0.6)

SYSTEMS WILL
REQUIRE $< 1\%$

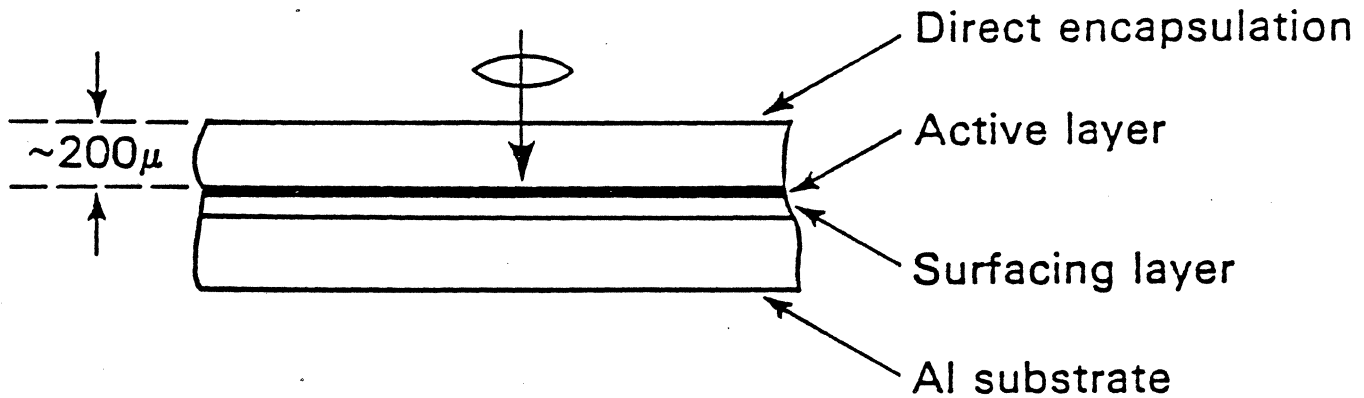
THICKNESS VARN.

IF 1mm AIR SANDWICH

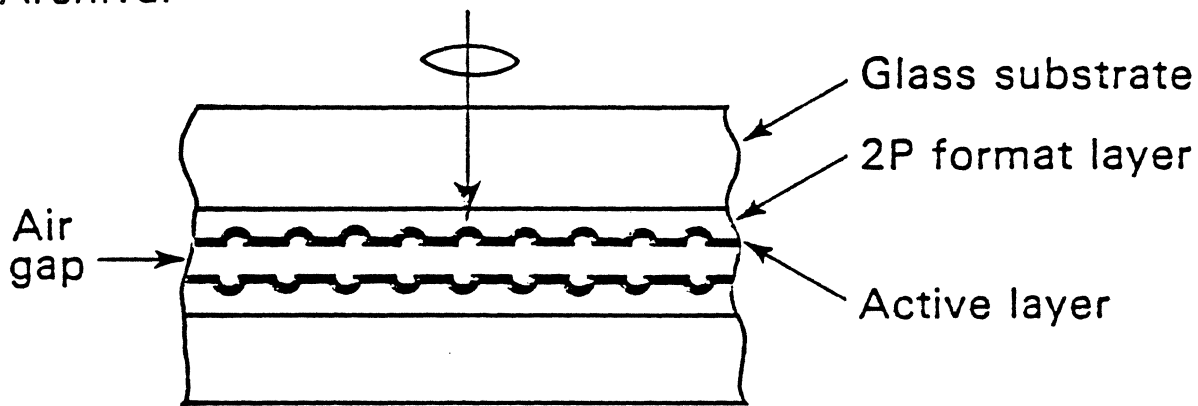
DESIGN IS USED

Disk Design

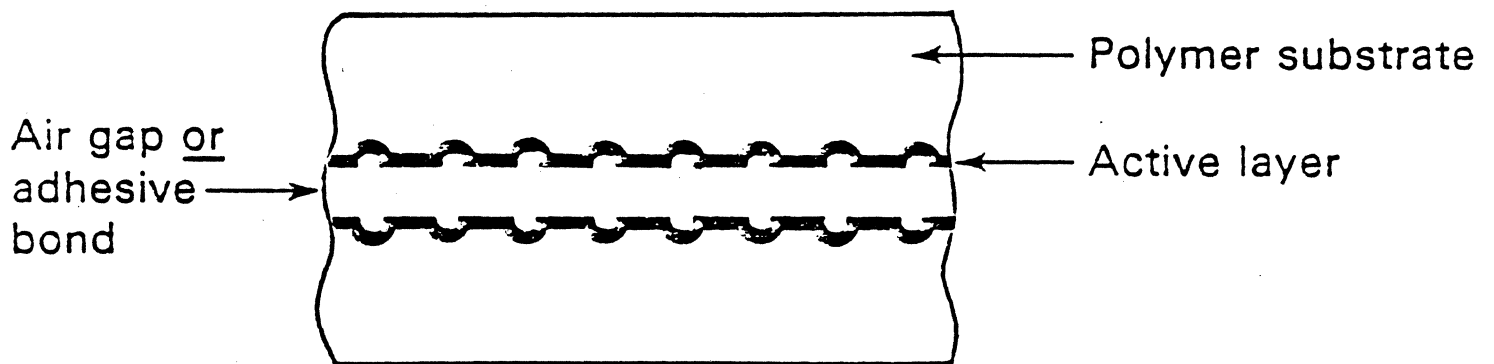
- High Performance



- Archival



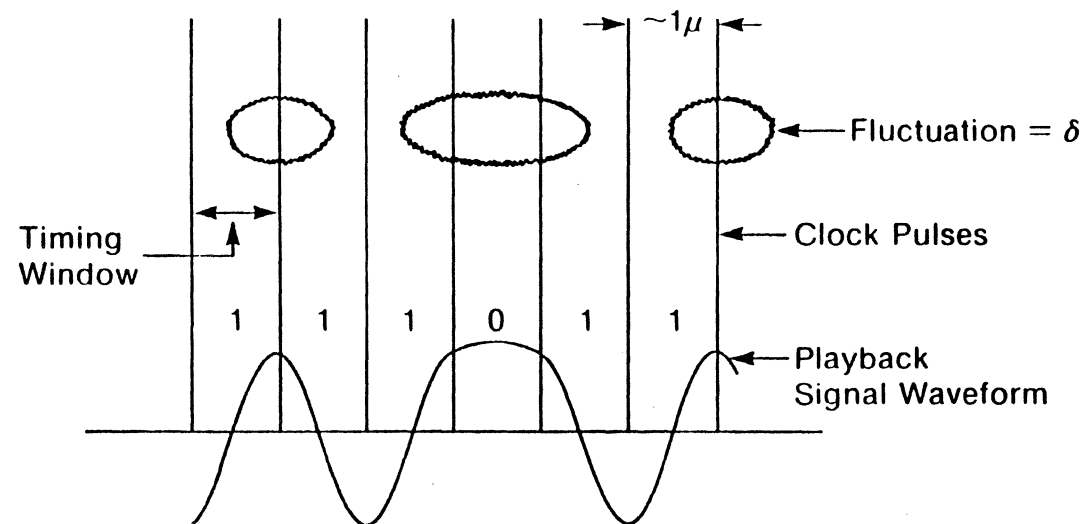
- Low cost



Active Layers

Basic Requirements of Read/Write Optical Storage Media

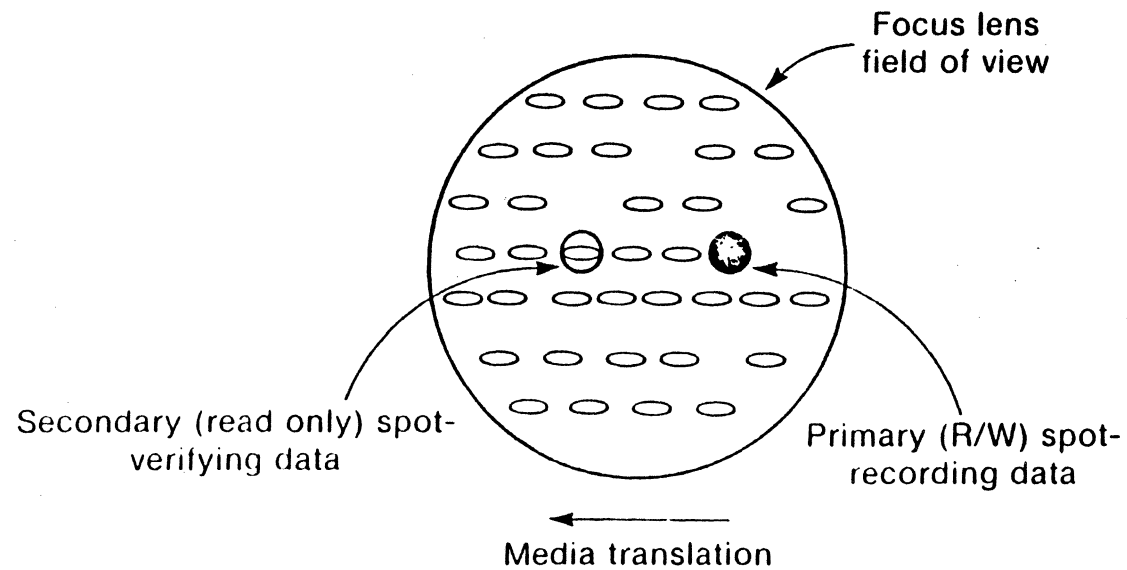
1. High Resolution and Regular Mark Geometry
 - To achieve adequate raw BER at high density



$$\delta \lesssim \pm 100\text{\AA} \text{ for BER} < 10^{-8} \\ \text{at } 10^8 \text{ b/cm}^2$$

Basic Requirements (cont.)

2. No Intermediate Processing
 - To permit data verification during recording

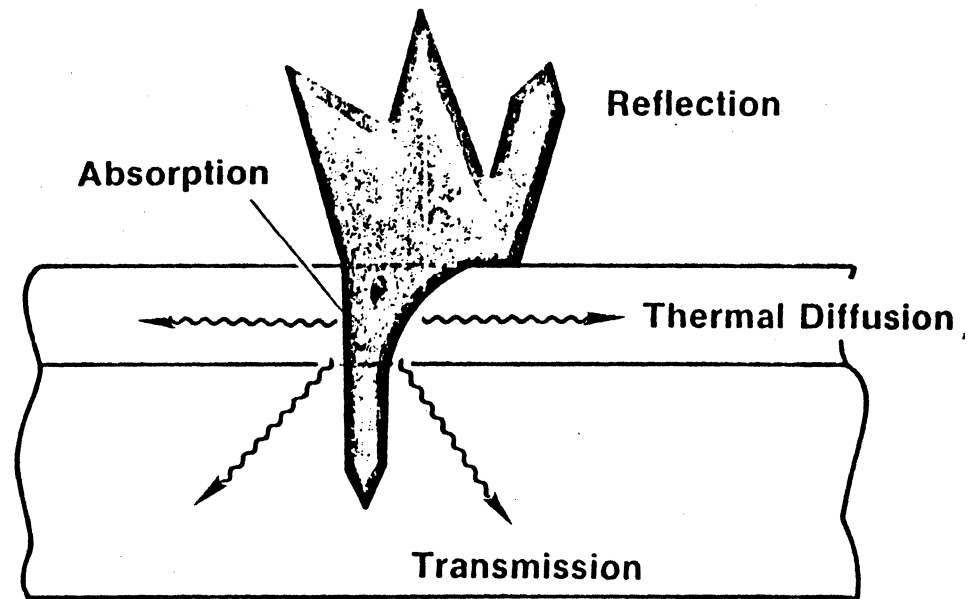


D-R-A-W Process

Basic Requirements (cont.)

3. High Sensitivity
 - To permit 1-3 MB/s with diode laser recording source
4. High Contrast Between Recorded Mark and Unrecorded Track
 - To maximize read signal amplitude (SNR)
5. Well Defined Threshold for Recording
 - To permit unlimited ($> 10^8$) reads without degradation

HIGH SENSITIVITY



High Absorption:

**Antireflecting designs (CF solar devices)
multilayer interference, texture**

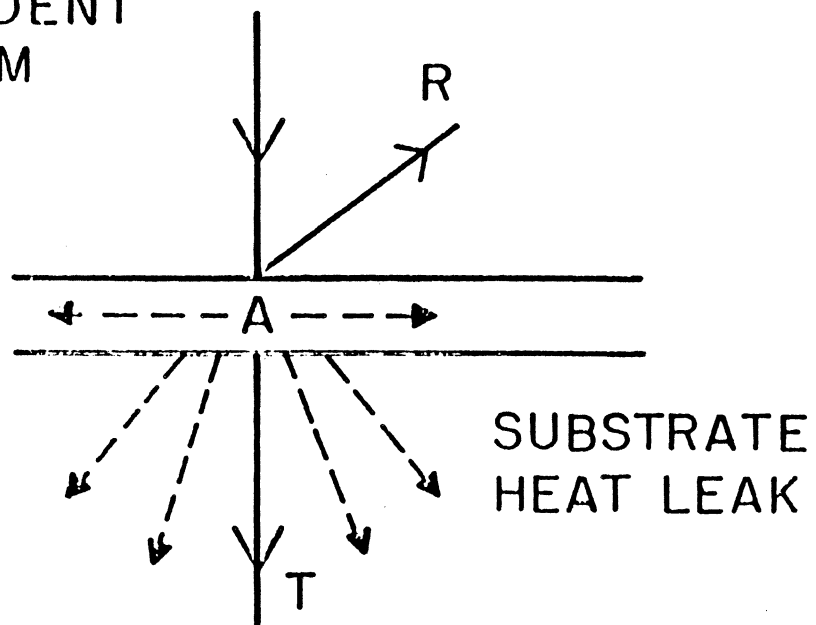
Low Heat Spread:

Low thermal diffusivity materials

Low Recording Energy:

**Low pit formation temperature and
latent heats**

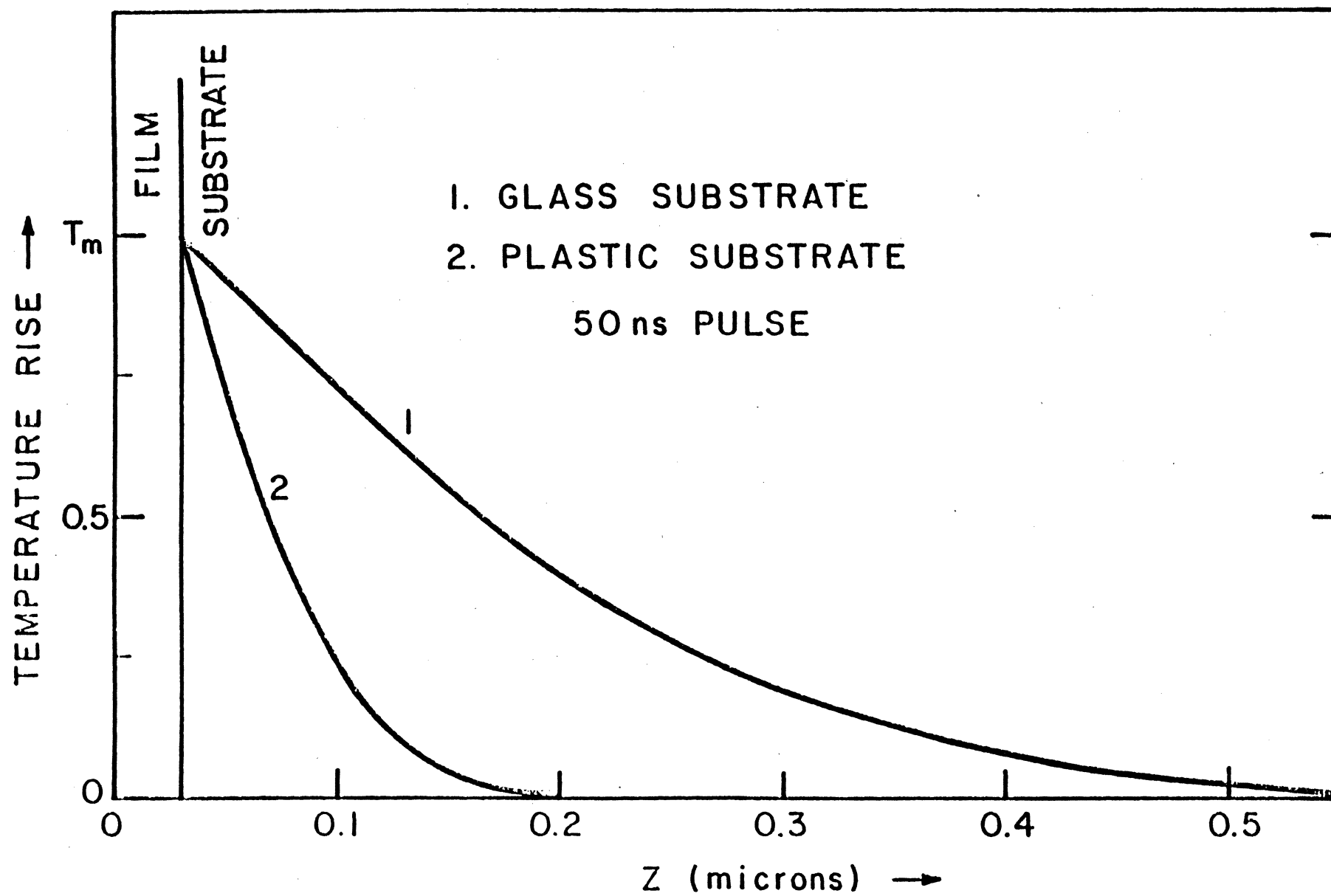
INCIDENT
BEAM



$$S \propto \frac{\eta_{\text{OPTICAL}} \eta_{\text{THERMAL}}}{Q_R}$$

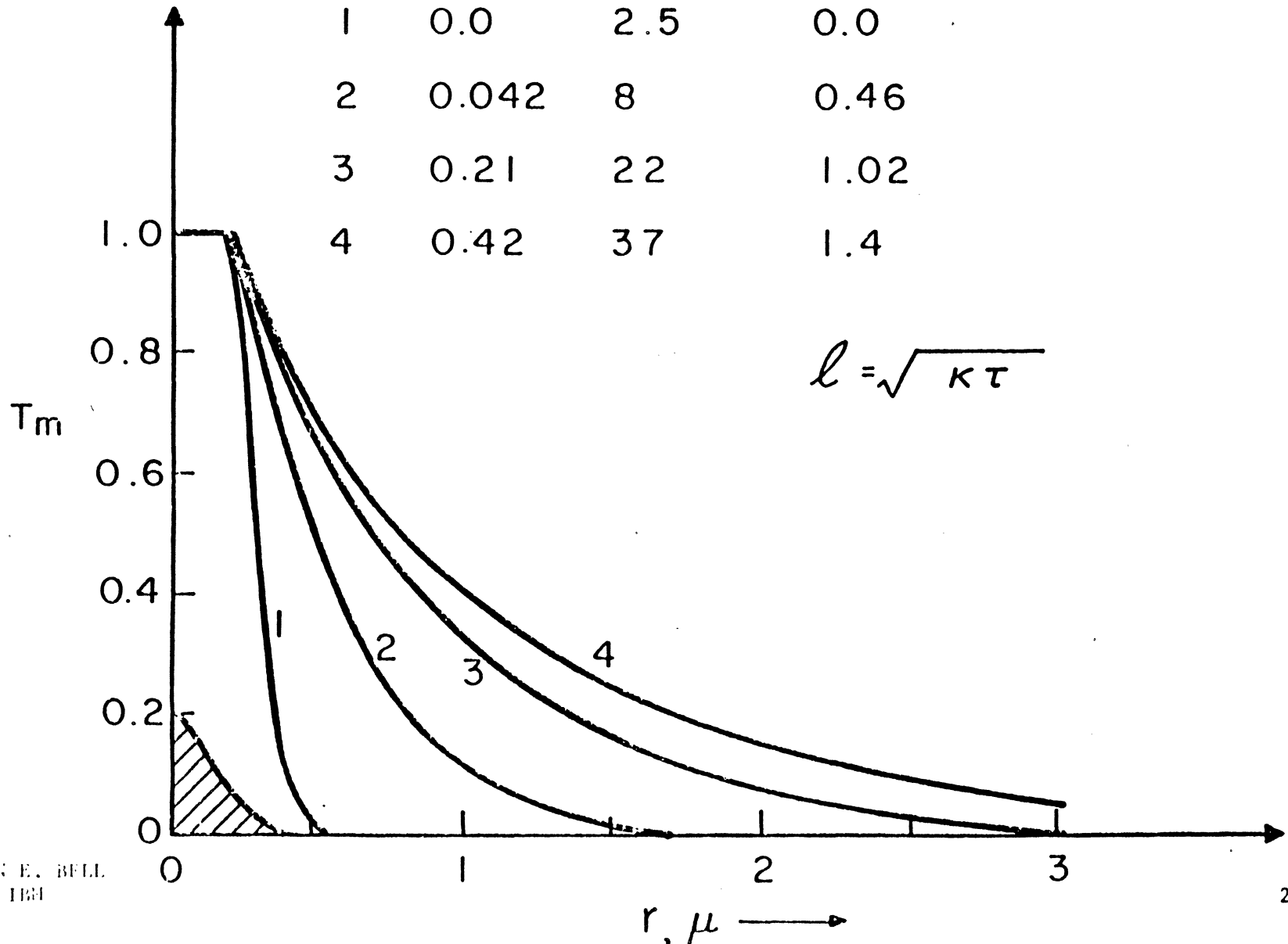
$$\eta_{\text{OPTICAL}} \longleftrightarrow n, k, d$$

$$\eta_{\text{THERMAL}} \longleftrightarrow \tau, K, \ell = \sqrt{K \tau}$$



ALAN E. BEIL
IBM

	κ cm ² /sec	P mW	ℓ μ
1	0.0	2.5	0.0
2	0.042	8	0.46
3	0.21	22	1.02
4	0.42	37	1.4



$$\ell = \sqrt{\kappa \tau}$$

*different
part*

Basic Requirements (cont.)

6. Stable Against Microcorrosion
 - To maintain low raw BER ($< 10^{-4}$) for at least 10 yr. lifetime
7. Compatible with Formattable Substrate
 - For track servo, sector ID, etc.
8. Compatible with Low Cost, High Volume Manufacturing Process

MACROSCOPIC MEASUREMENTS ARE NOT SENSITIVE TO MICROSCOPIC DEFECTS

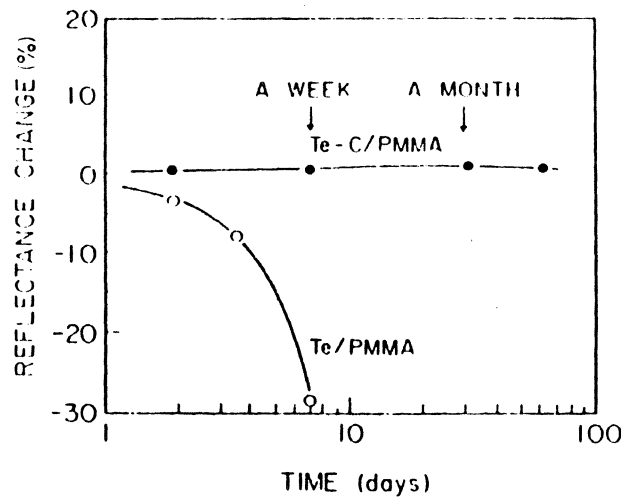
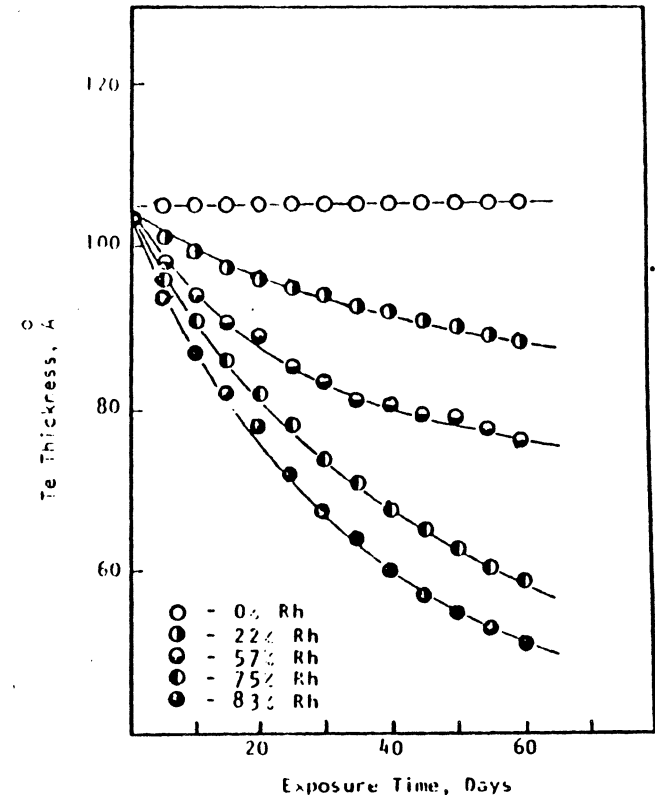


Figure 4. Reflectance degradation comparison for a Te-C disk (Te-C/PMMA) and Te disk (Te/PMMA) under 70°C, 85% RH stressed conditions. Reflectance measurements were carried out at a 633 nm wavelength.

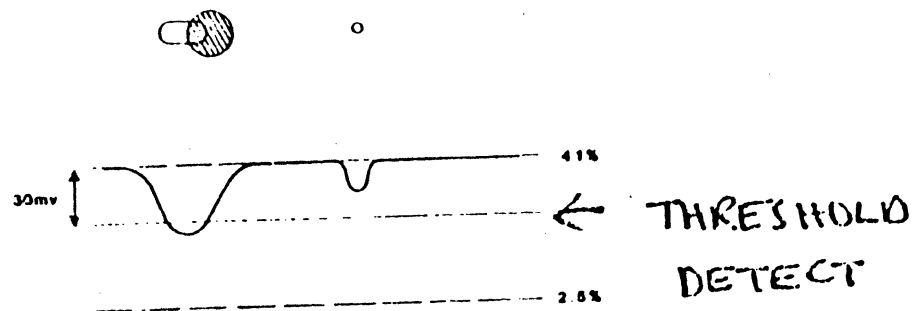
Figure 1. Time-dependence of Te thickness for unprotected Te at 0, 22, 57, 75 and 83% Rh.



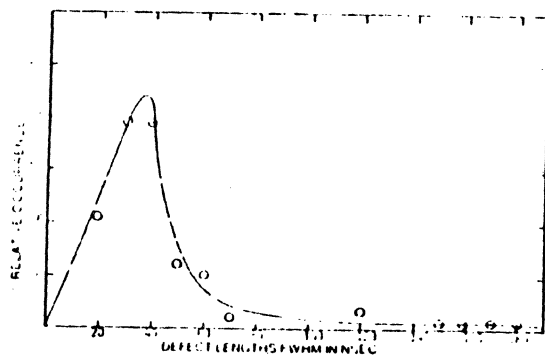
eg BER 10^{-2} ALL $1/\mu^2$ HOLES
HAS 1% IMPACT ON LARGE AREA
REFLECTIVITY OR TRANSMISSION

DEFECT SCANS

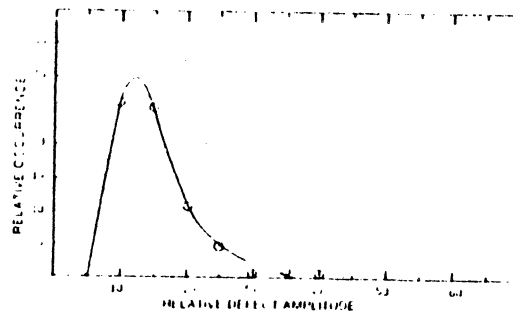
(1) PRINCIPLE



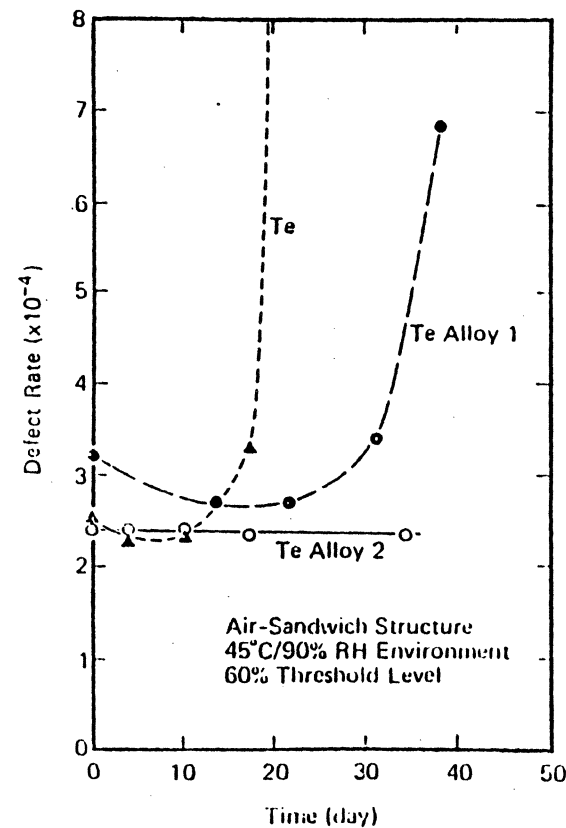
(2) CAN OBTAIN STATISTICS NECESSARY FOR E.C.C. DESIGN



W13 Fig. 1 Defect length vs occurrence in Te-trilayer optical recording media.



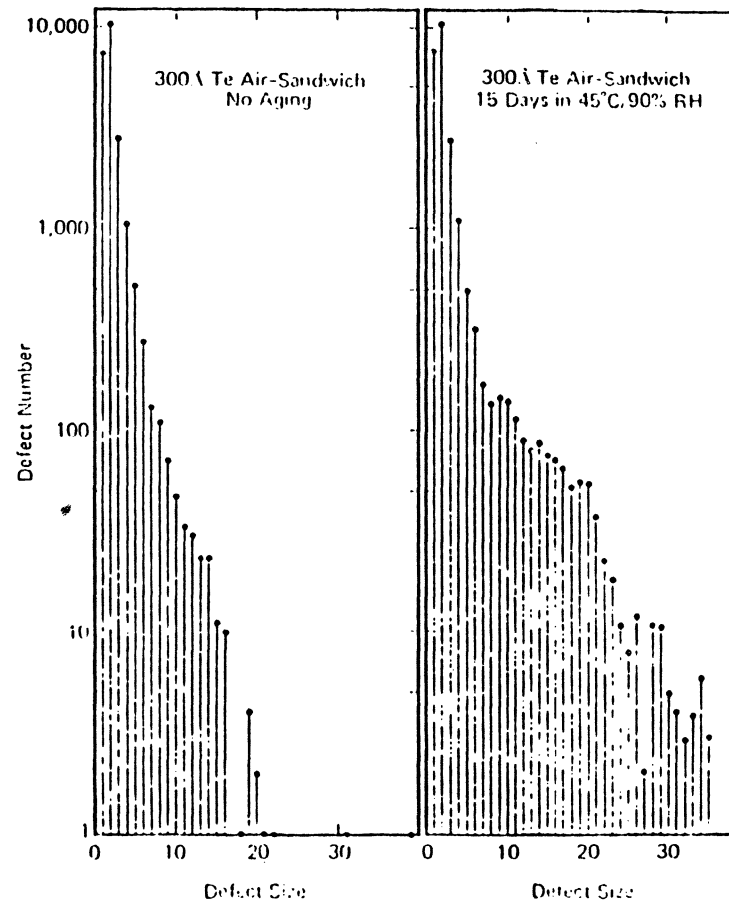
W13 Fig. 2 Defect amplitude vs occurrence in Te-trilayer optical recording media.



LDU N.A. PHILIPS
CHEN, MARRELLO IBM

EFFECT OF AGEING ON DEFECT SIZE DISTRIBUTION

(Marrello & Chen, IBM)

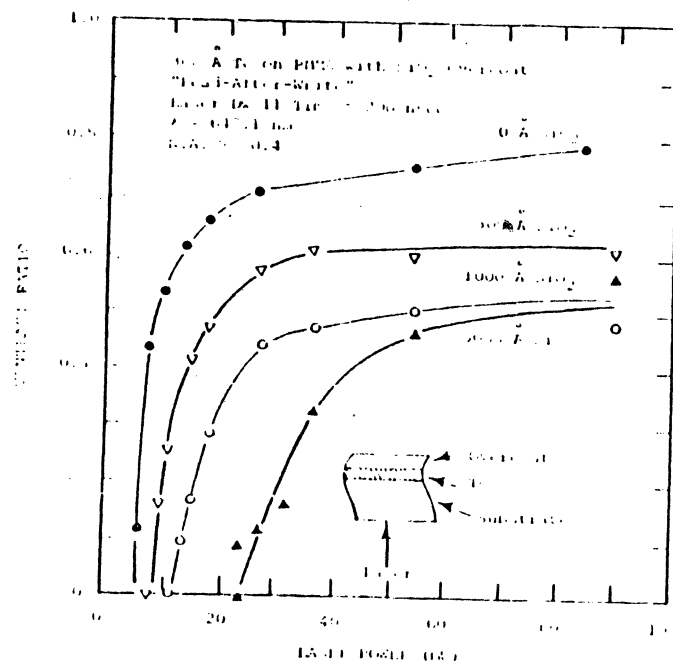


MARRELLO, CHEN IBM

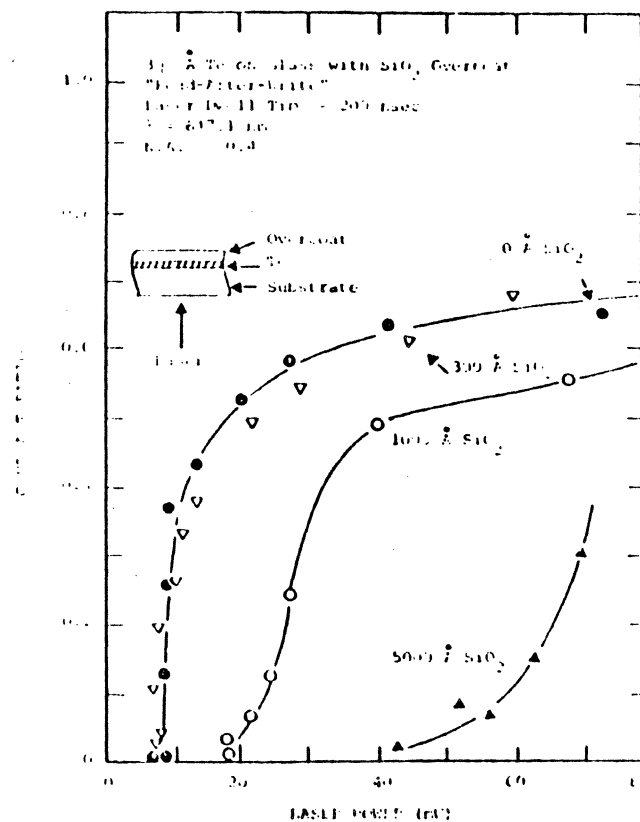
IMPACT OF PASSIVATION LAYERS

CAN BE SEVERE IF MATERIALS
AND RECORDING MECHANISM ARE NOT
COMPATIBLE

CONTRAST RATIO ON IRMA SUBSTRATES
WITH VARYING THICKNESSES OF SiO_2 OVERCOATING

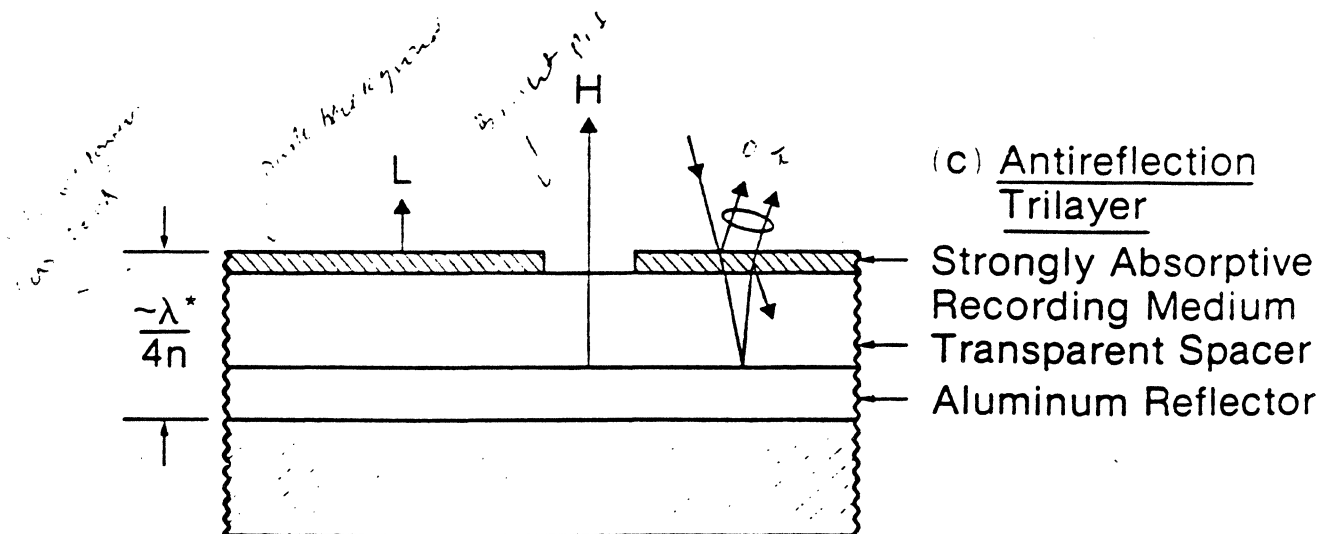
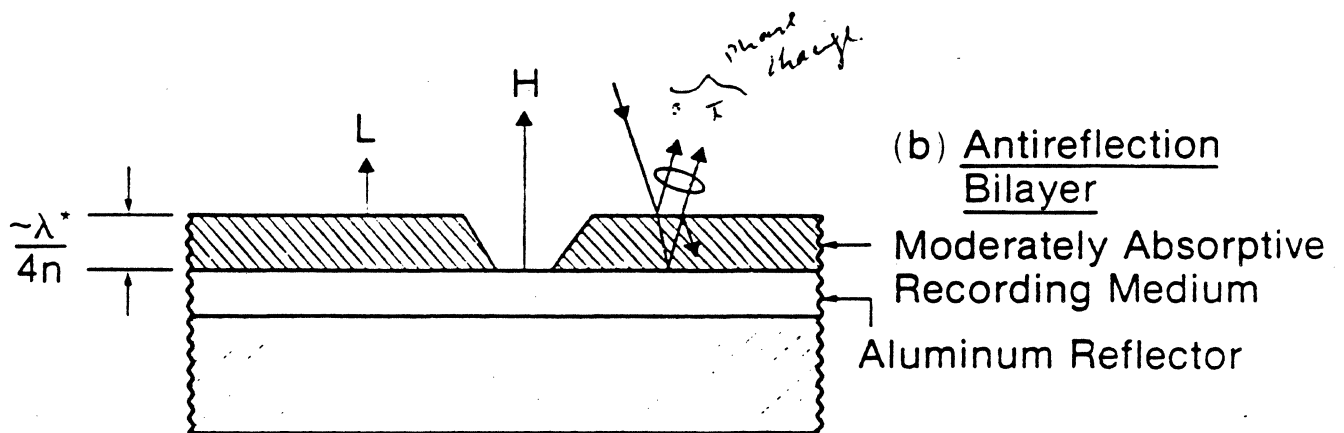
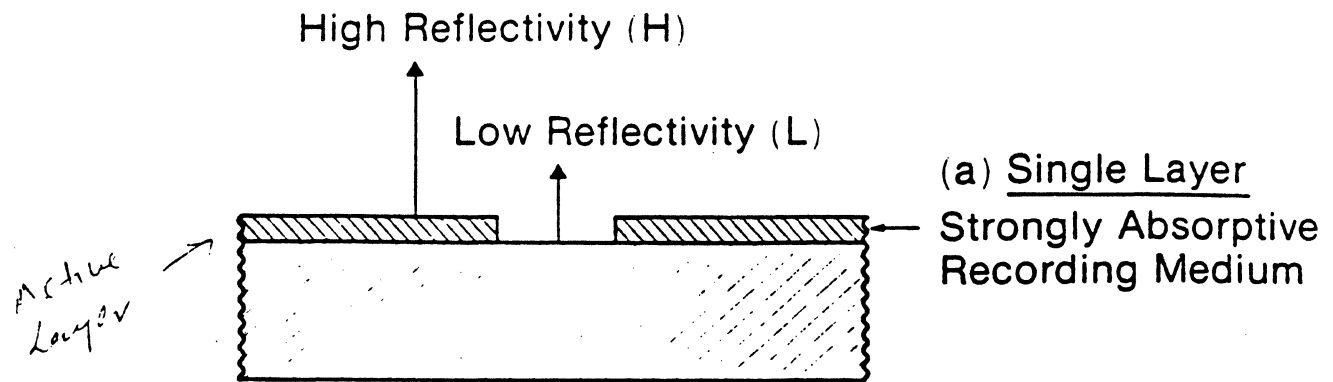


CONTRAST RATIO ON GLASS SUBSTRATES
WITH VARYING THICKNESSES OF SiO_2 OVERCOATING



THE MEDIA MUST BE INTRINSICALLY AS STABLE
AS POSSIBLE

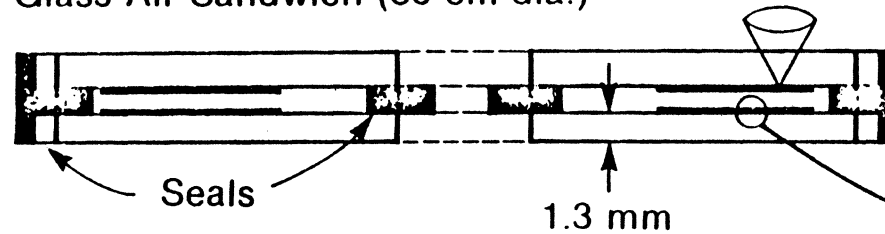
Anti-reflection structures.



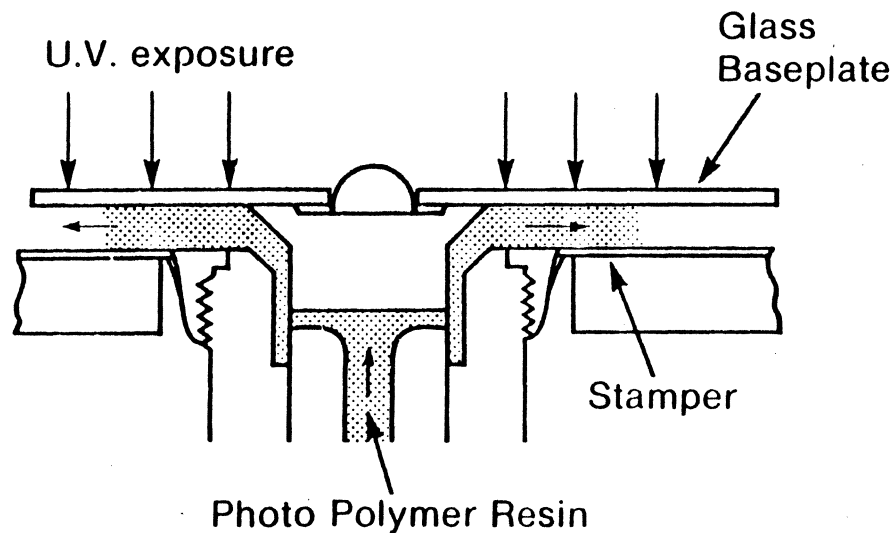
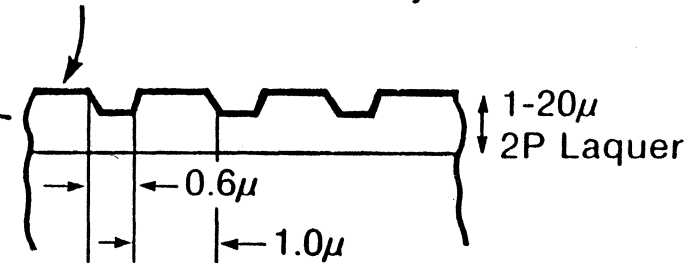
* $\frac{\lambda}{4n} \sim 100\text{nm}$ typically when $\lambda = 800\text{nm}$

Single Layer Te-Alloy Media

Glass Air Sandwich (30 cm dia.)



30 nm TeSe-based alloy



2P-process for
substrate formatting

Characteristics of Philips DOR Media

Capacity	2.4 GB/disk
Data Rate	2.4 Mb/s (480 rpm)
Record Pulse	60 ns, ~10 mW
Playback SNR	55 dB (30kHz)
Raw BER	$<10^{-5}$
Lifetime	>10 yrs

Huijser et al, OML (1983)

laser power ~ 50 W
laser process ~ 100 W

ELEMENTS OF MELTED HOLE FORMATION

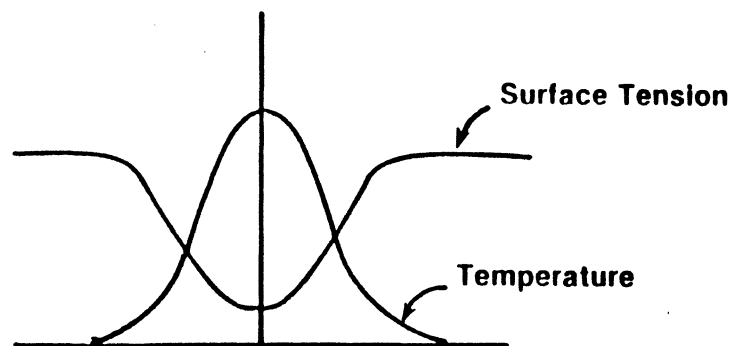
- 1) **Pre-Initiation:** Laser energy absorbed to elevate film temperature to or above melting point
- 2) **Initiation:**
 - Vaporization of substrate, ruptured blister
 - Vaporization of film
 - Surface tension gradients (Marangoni Effect)
 - Recoil pressure gradients
 - Surface microroughness
 - Film microvoids
 - Substrate microroughness
- 3) **Formation:**
 - Surface tension
 - Viscous reaction forces

HOLE INITIATION MECHANISMS

Substrate Vaporisation

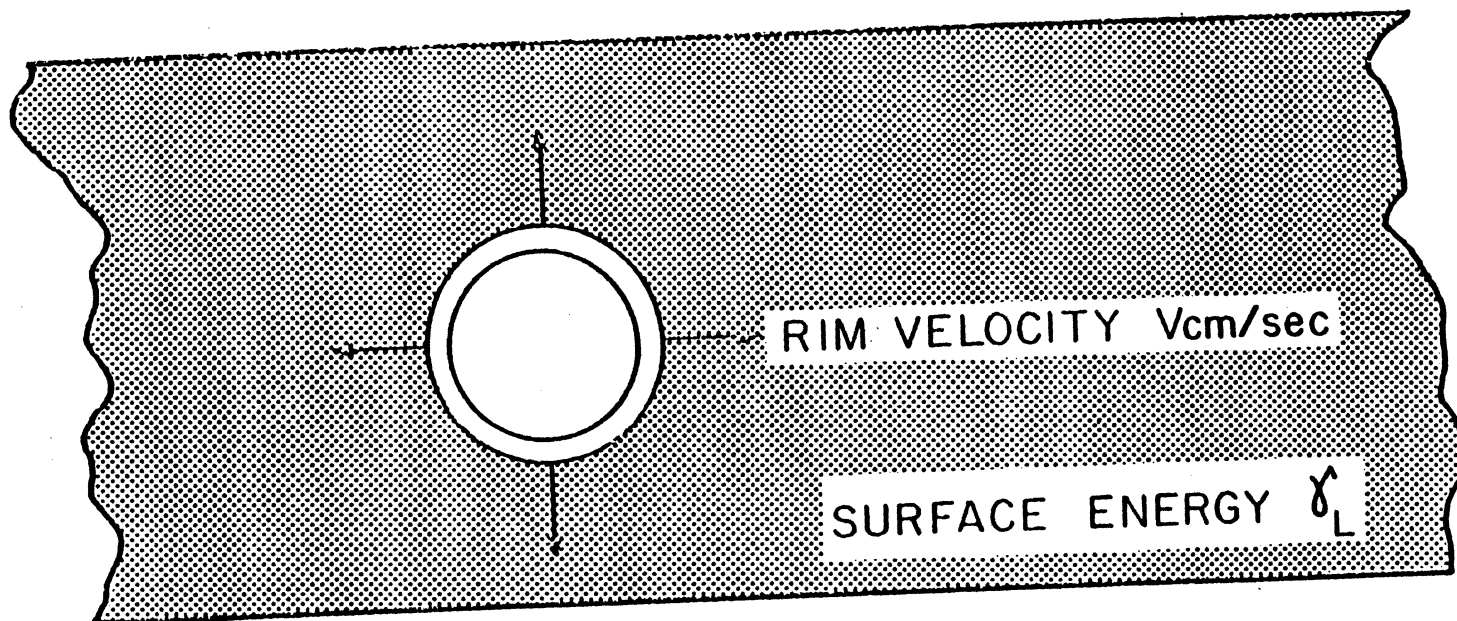
Surface Microroughness

Surface Tension Gradients



$$F \propto r \frac{\partial \gamma}{\partial r}$$





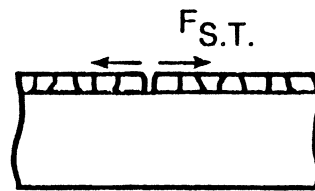
PUNCTURED MEMBRANE, THICKNESS d cm, DENSITY ρ

$$V = \sqrt{\frac{2\gamma}{\rho d}} \text{ cm/sec}$$

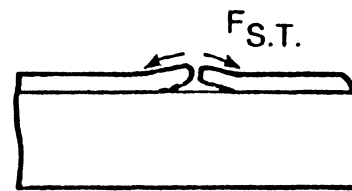
eg $V_{Te} \approx 5000 \text{ cm/sec}$ ($d=30\text{nm}$)

HOLE FORMATION IN Te FILMS

2) Initiation



a) Polycrystalline Te
 $P_{\text{THRESH}} \approx 8\text{mW}$
(100ns pulse)



b) Amorphous $\text{Ge}_{15}\text{Te}_{85}$
 $P_{\text{THRESH}} \approx 18\text{mW}$
(100ns pulse)

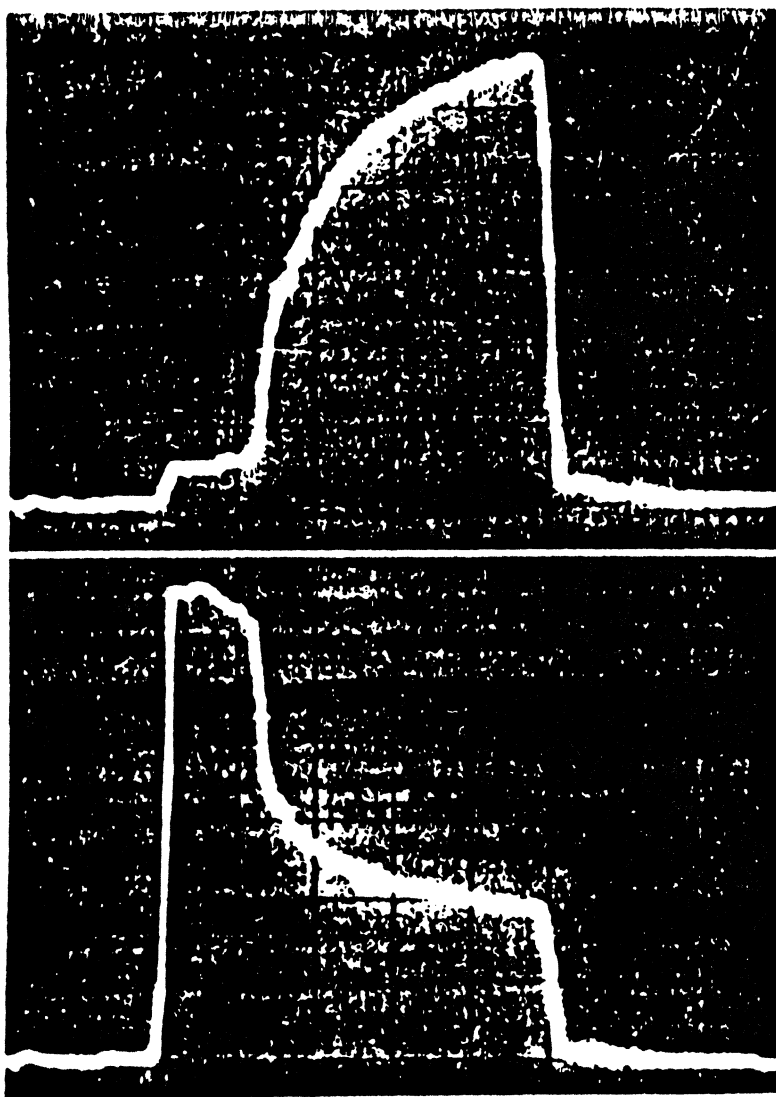


Fig. 5a and b. Oscilloscope traces of the transmitted (a) and reflected (b) laser beam during exposure of a 31.5 nm tellurium film on PMMA. (Power: 5 mW, wavelength: 530 nm and $r_A = 1.22 \mu\text{m}$, horizontal scale: $0.2 \mu\text{s}/\text{div}$)

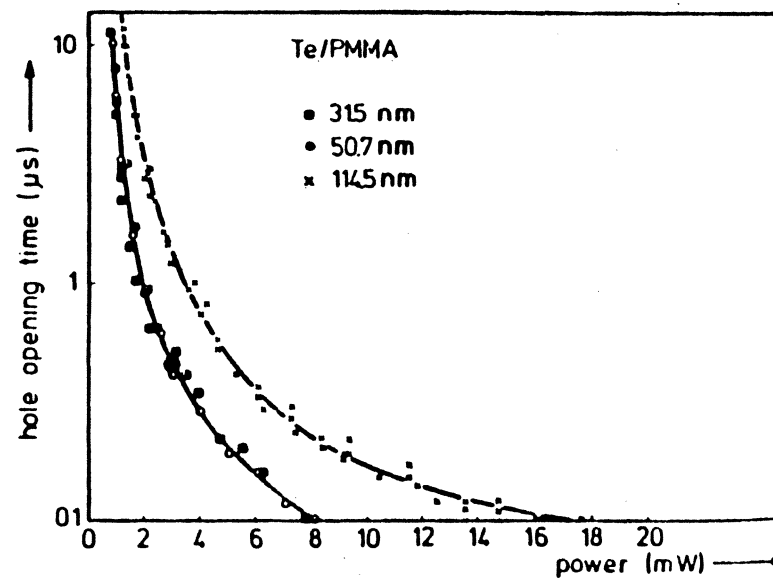


Fig. 6. Hole opening time versus power for Te films of different thickness. (Wavelength: 530 nm, $r_A = 1.22 \mu\text{m}$)

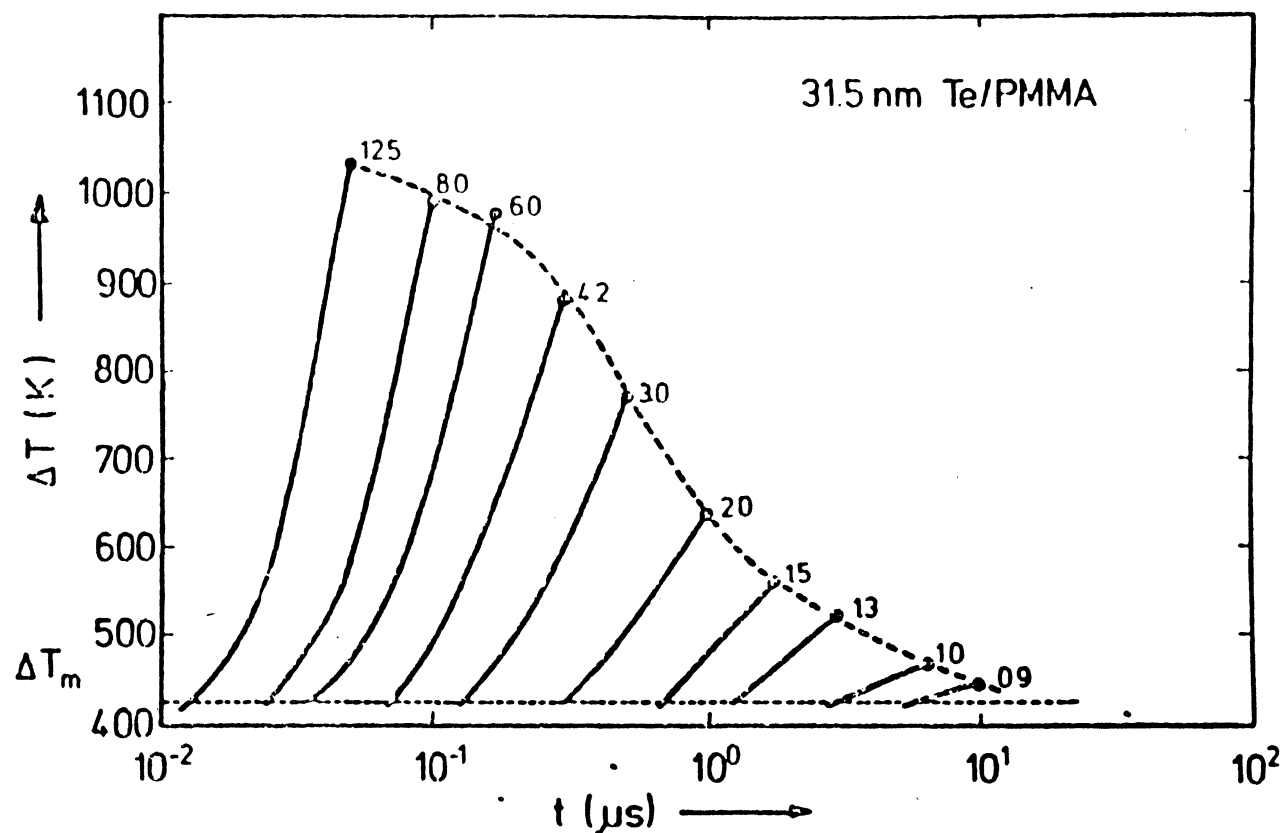


Fig. 7. Numerically calculated temperature rise of a 31.5 nm Te film on PMMA in the centre of the spot for different laser powers [mW]. (Wavelength: 530 nm, $r = 1.22 \mu\text{m}$). Only the part above the melting point is shown. The dashed curve connects temperatures just before hole opening for different threshold powers

Sub-oxide layers (MATSUSHITA)

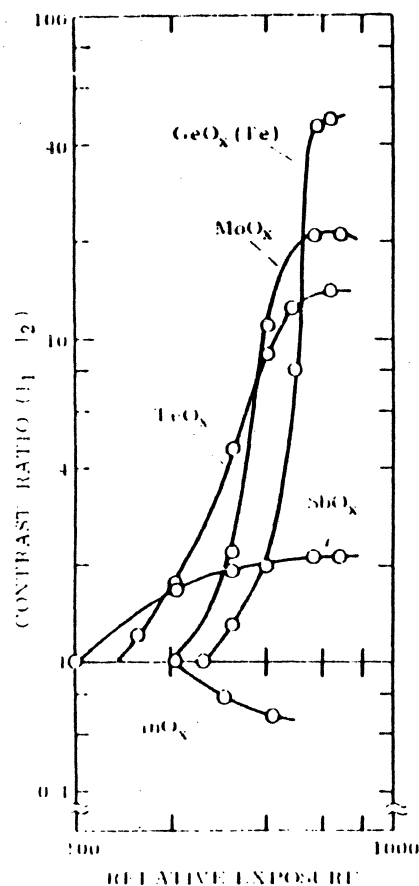


Figure 1. Transmission contrast ratios of sub-oxide thin films before to after Xe flash exposure as a function of exposure power.

AKAHIRA et al
SPIE 329, 195(82)

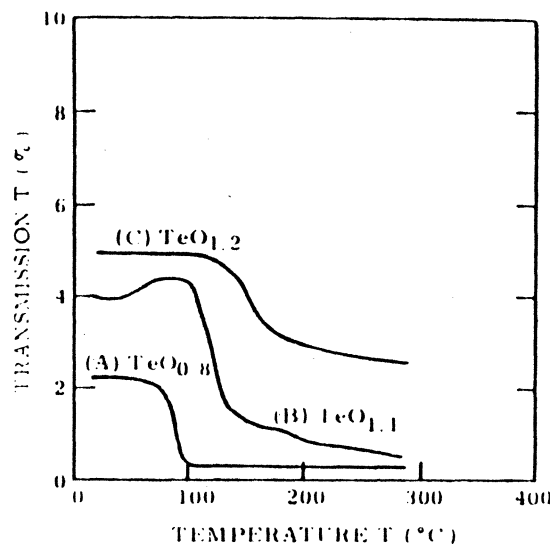
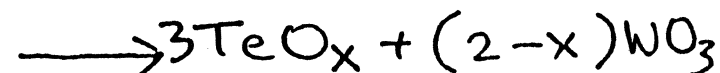


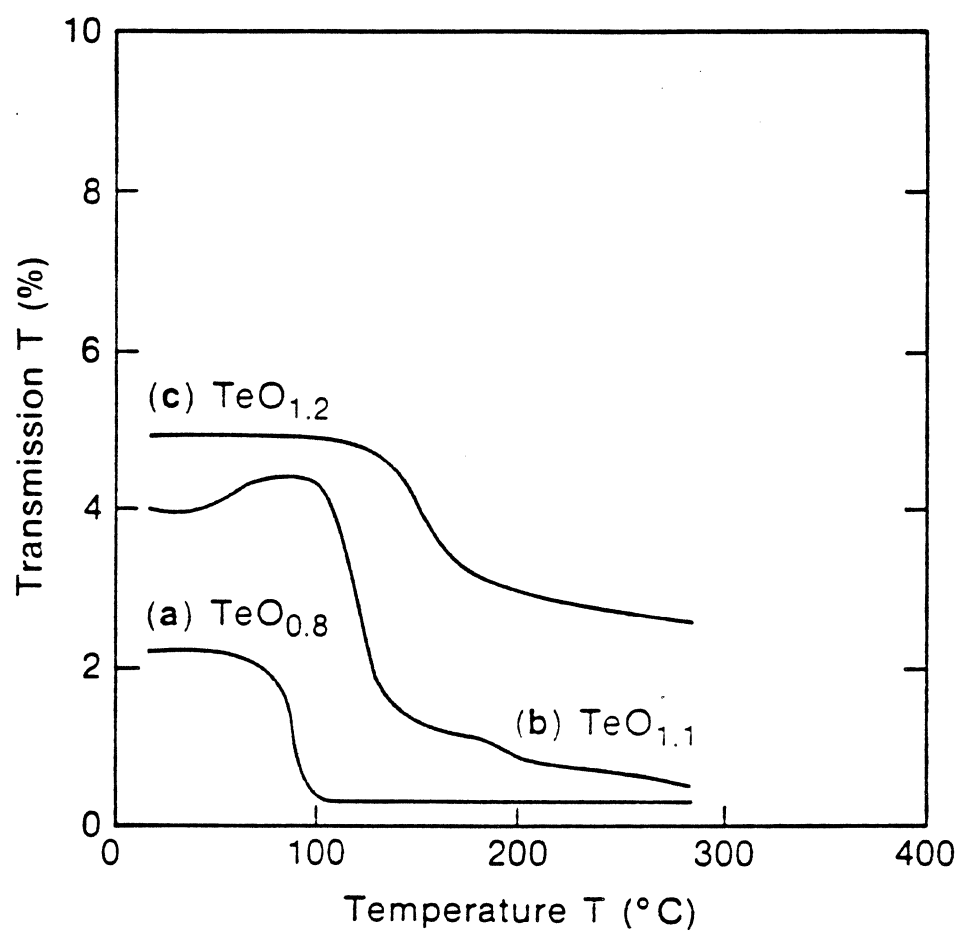
Figure 4. Transmission changes of thin films TeO_x by heating.

Table 2 Color changes of sub-oxide thin films induced by a flash light exposure.

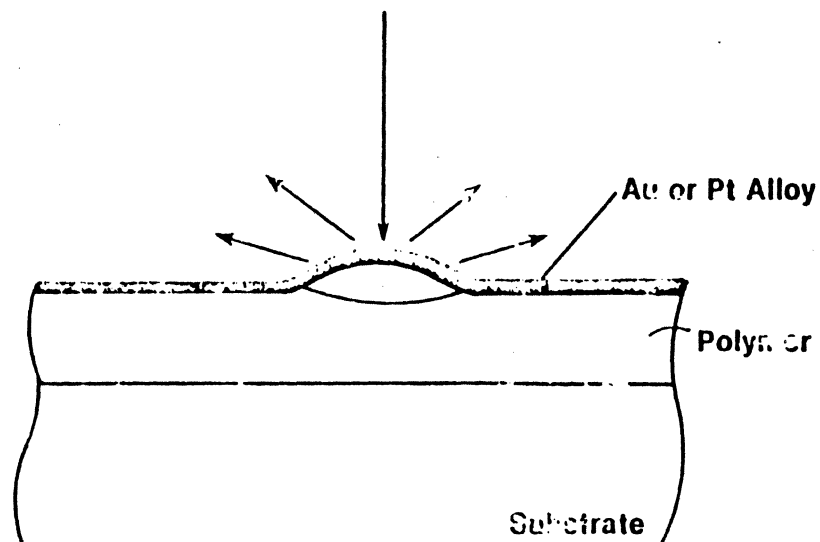
InO_x	Gray	→ Whiten
$\text{GeO}_x(\text{Te})$	Yellow, Brown	→ Darken
PbO_x	Gray, Brown	→ Darken
SbO_x	Gray, Brown	→ Darken
TeO_x	Gray, Brown	→ Darken
K_2O_x	Blue	→ Blue black

VACUUM EVAPORATION OF POWDER MIXTURE
OF TUNGSTEN(DE-OXIDISING AGENT) AND TeO_2





THOMSON-CSF BUBBLE MODE MEDIUM

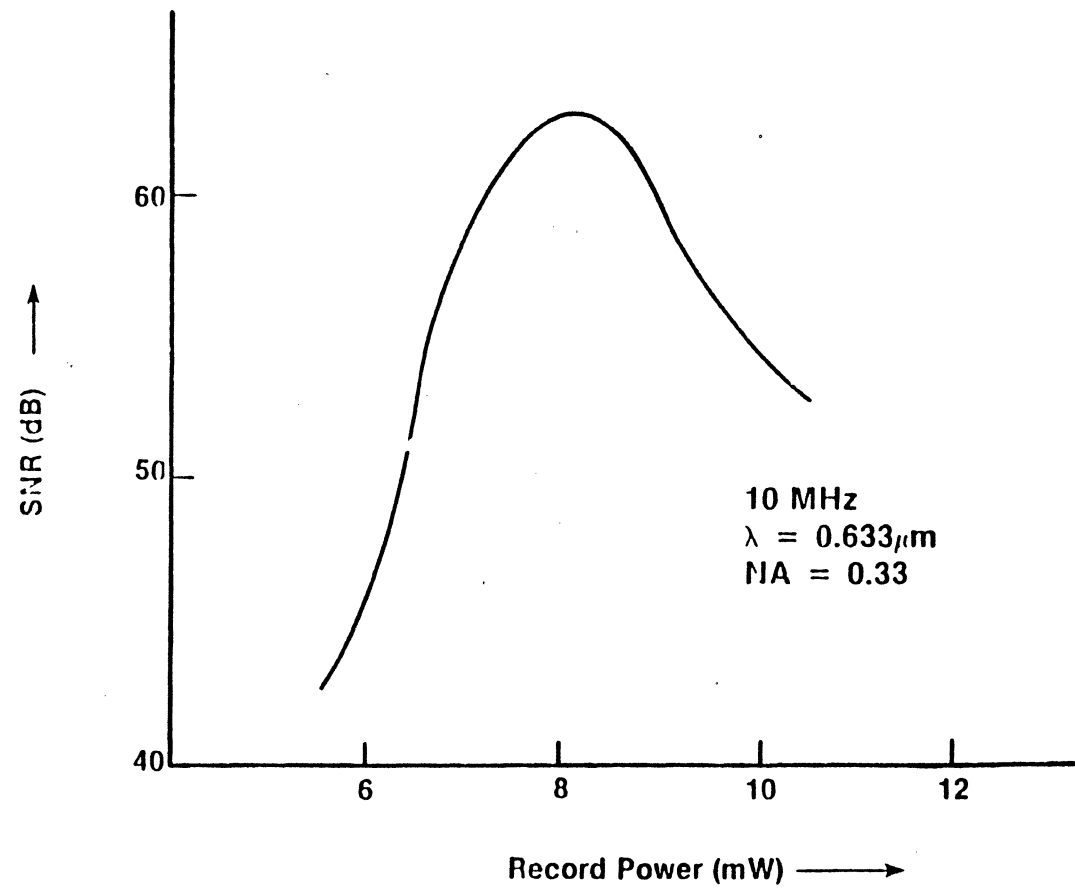


Advantages

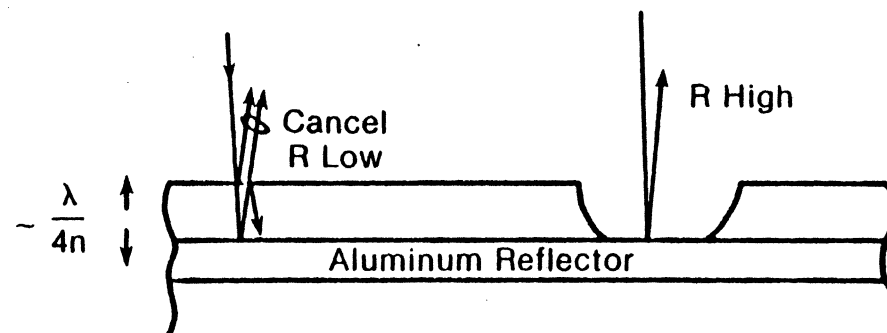
- 1) High Sensitivity Without Low M.Pt. Metals
- 2) High SNR—No Irregular Melted Rims
- 3) Can Be Replicated

J. CORNET et al
CLEO'81 PROC. 122

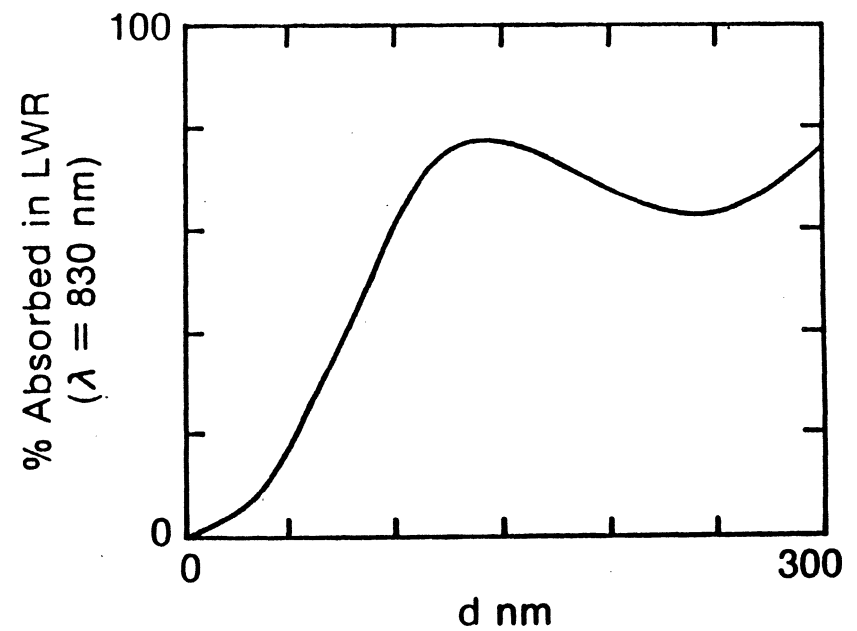
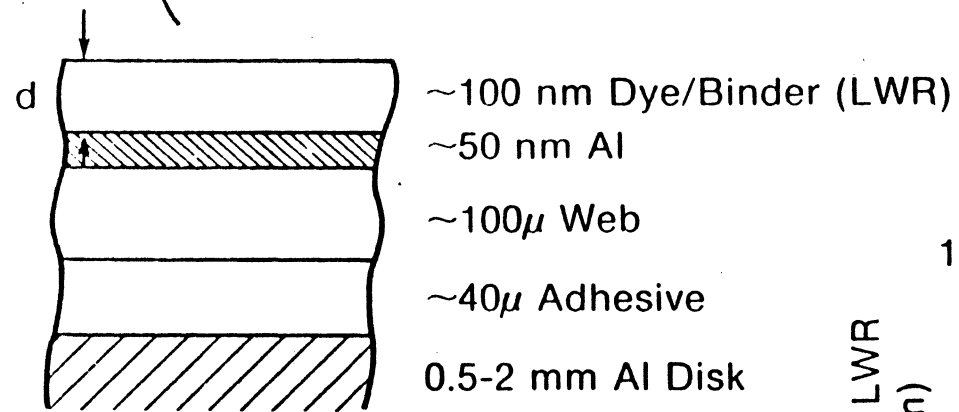
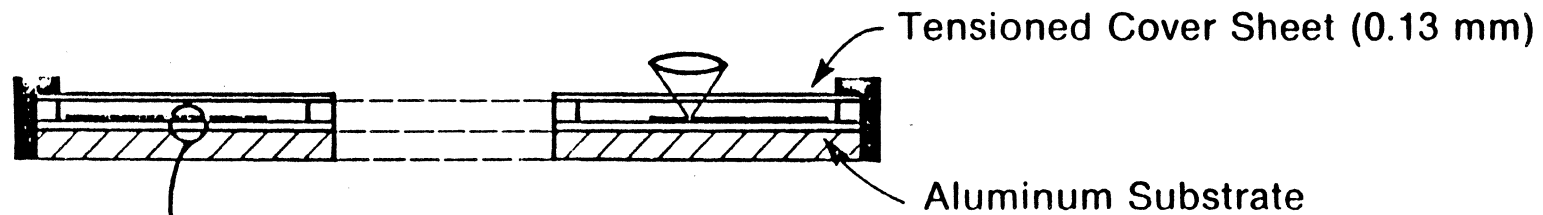
THOMSON-CSF MEDIUM



**ANTIREFLECTION BILAYER (RCA)
—FOR MODERATELY ABSORPTIVE MATERIALS**



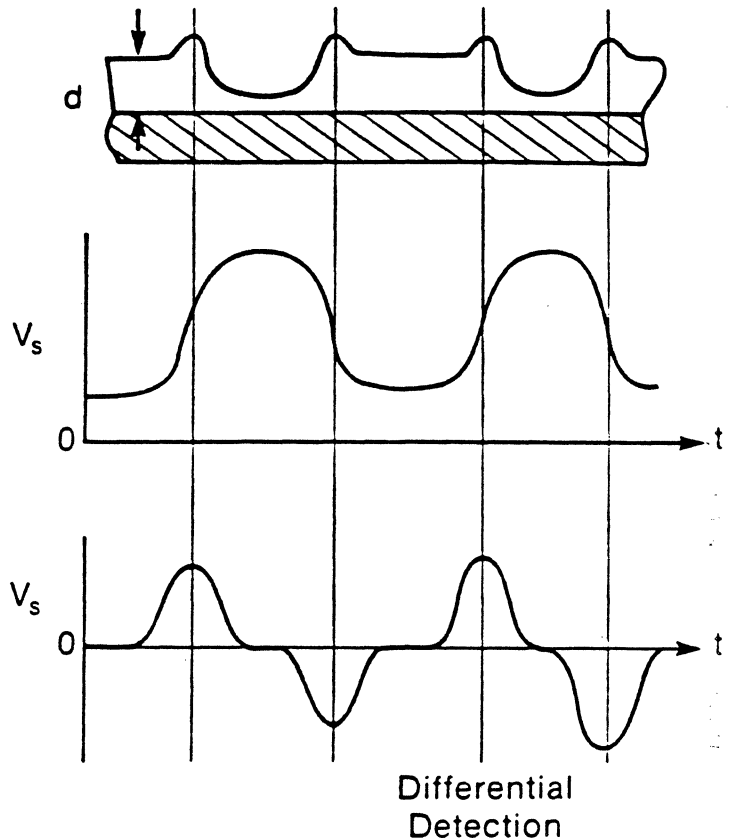
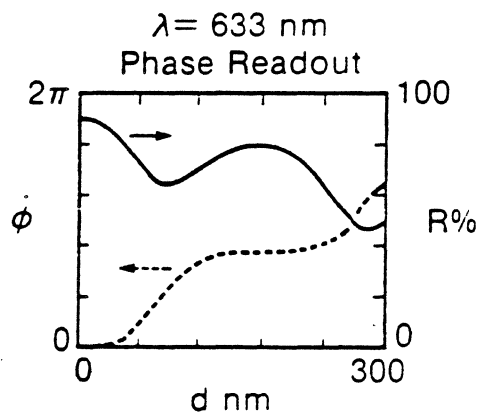
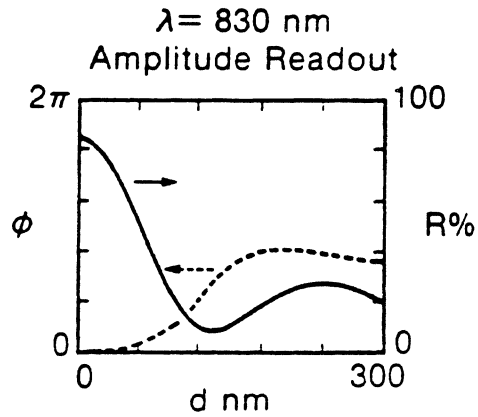
Dye/Binder Bilayer (Kodak)



Howe et al, Kodak

ALAN E. BELL
IBM

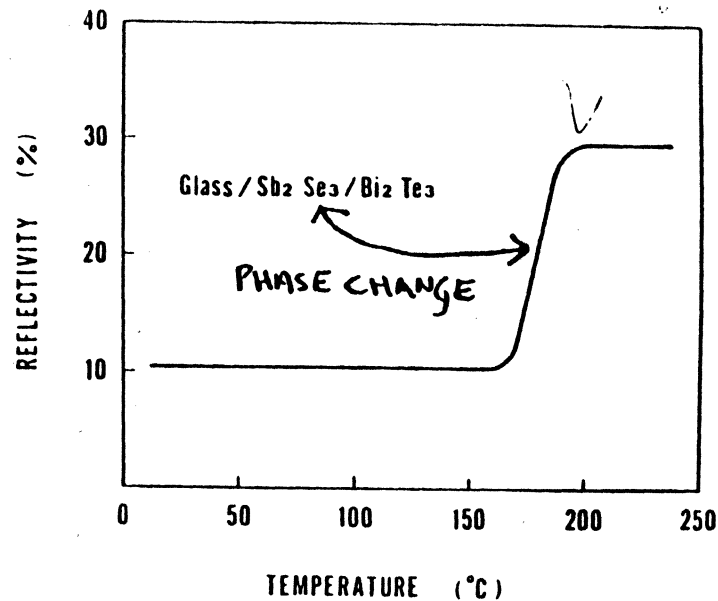
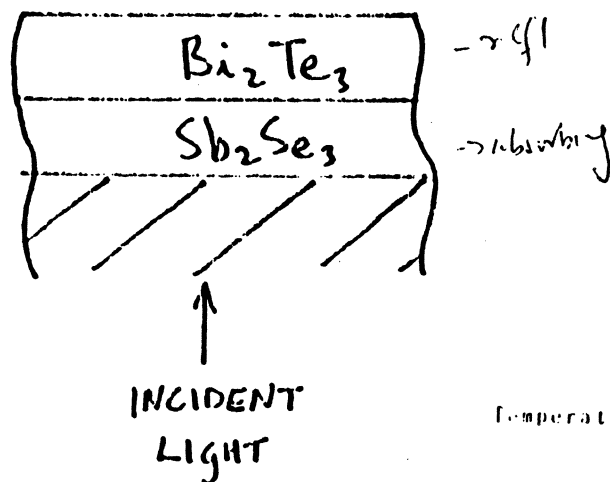
Characteristics of Dye/Binder Media



Capacity	5.8 GB
Data Rate (1800 rpm)	~2 MB/s
Record Power	60 ns, 10 mW
Playback SNR	70 dB (30 kHz) $\lambda=633 \text{ nm}$
	60 dB $\lambda=830 \text{ nm}$
Raw BER	$<10^{-5}$
Lifetime	$>10 \text{ yrs}$

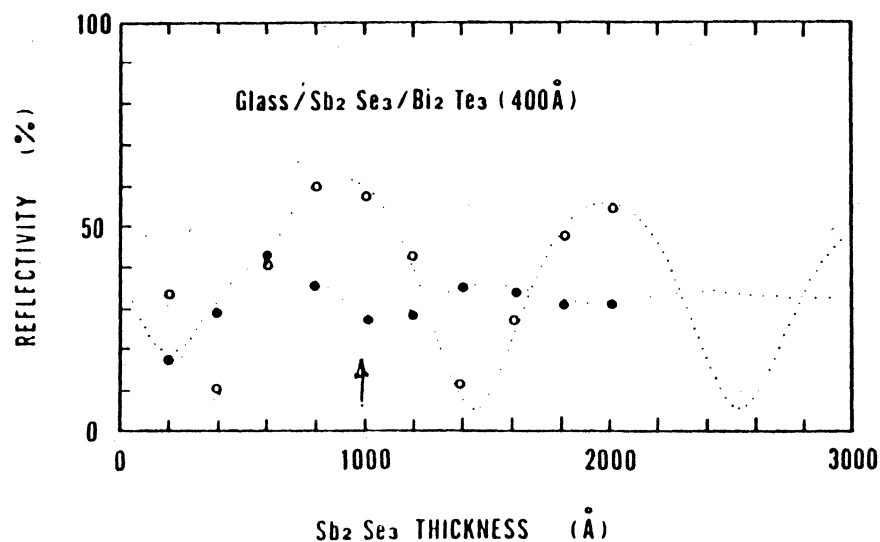
Howe et. al., Kodak (1983)

SONY MEDIA



will only be
not reversible)

Temperature dependence of reflectivity of a 100 Å Sb_2Se_3 film on a 100 Å Bi_2Te_3 film.



as reported (amorphous)

after heating / crystallization

interference effects.
(used to check the
thickness)

Fig.2 Thickness dependence reflectivity of Sb_2Se_3 on a 400 Å Bi_2Te_3 layer.
○ : experimental results of the films before heat treatment. ● : after heat treatment.
The dotted lines are theoretical curves.

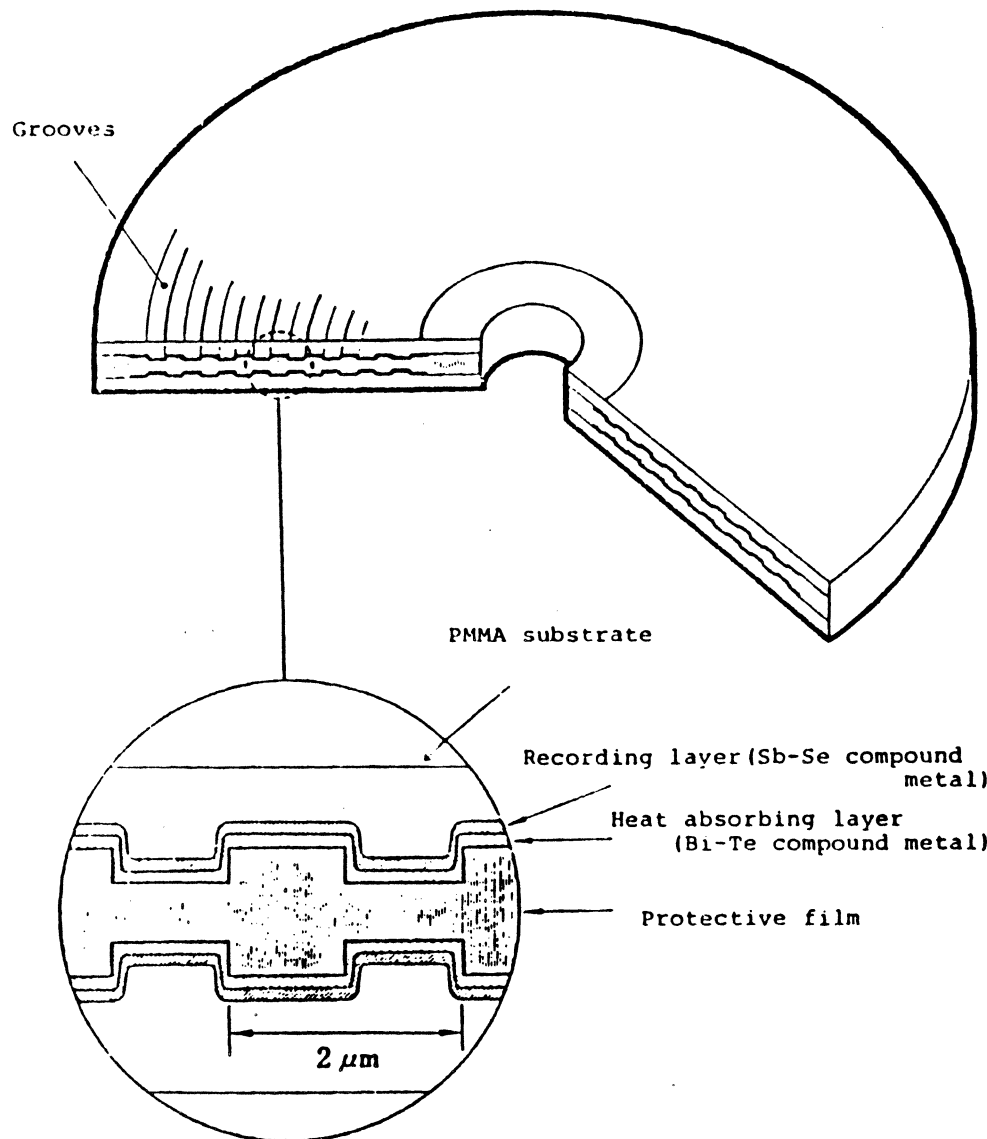


Fig.4 The structure of a double-sided disc.

VIDEO RECORDING

$$f = 5.5 - 7 \text{ MHz}$$

1800rpm

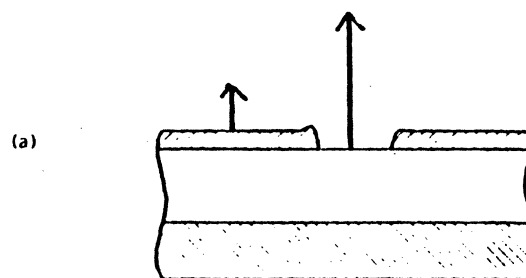
Diode laser

0.9μ diameter spot

$P = 4\text{mw}$ RECORDING

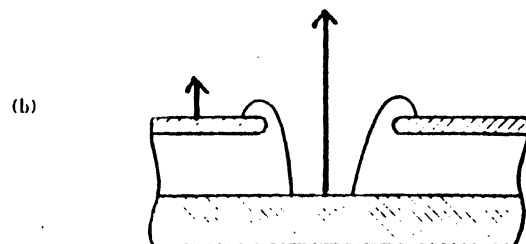
$\text{SNR} = 60\text{dB}$ PLAYBACK
(10kHz BW)

RECORDING MODES
IN THE TRILAYER
STRUCTURE (RCA)



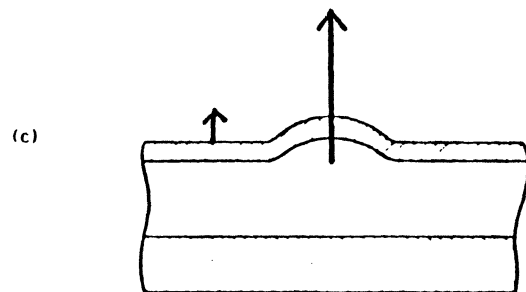
STANDARD MODE

RCA, KODAK, IBM



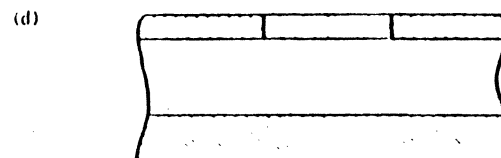
DEEP PIT MODE

RCA



BUBBLE MODE

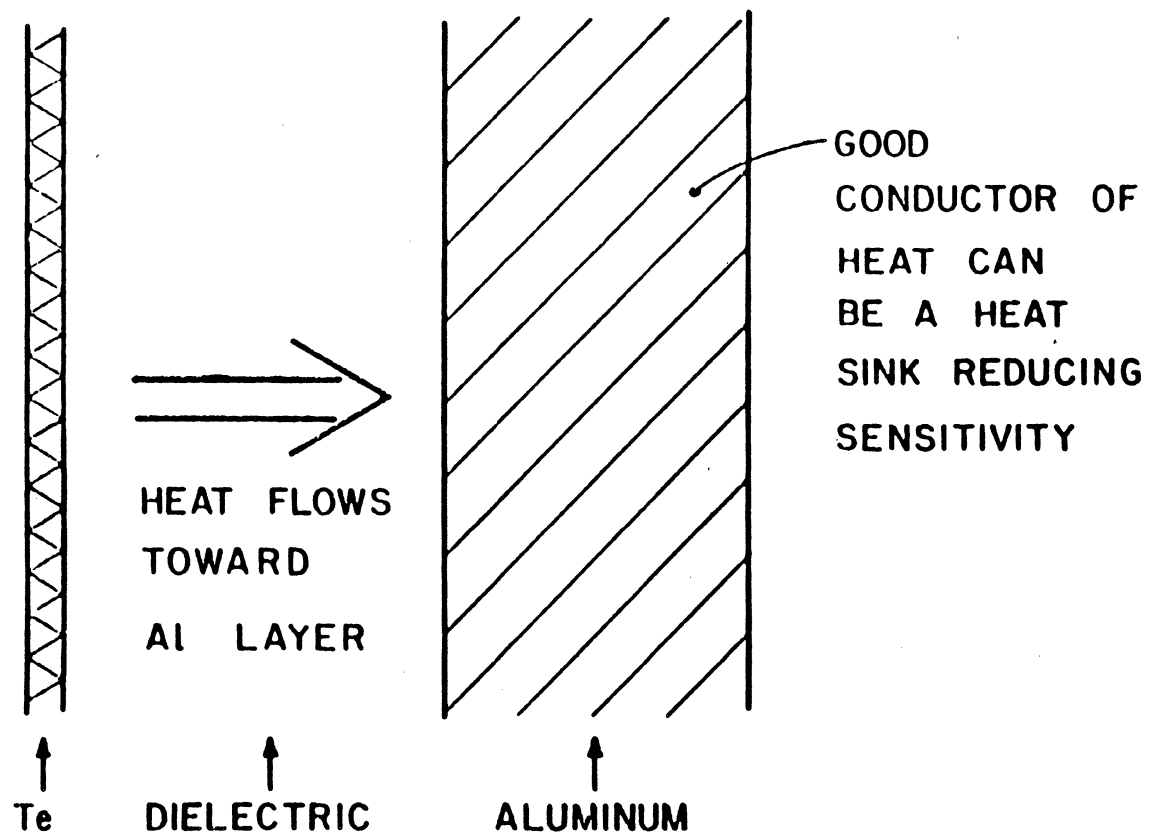
RCA, 3M, XEROX,
THOMSON CSF



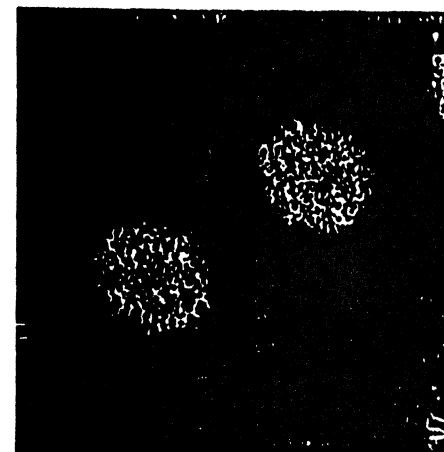
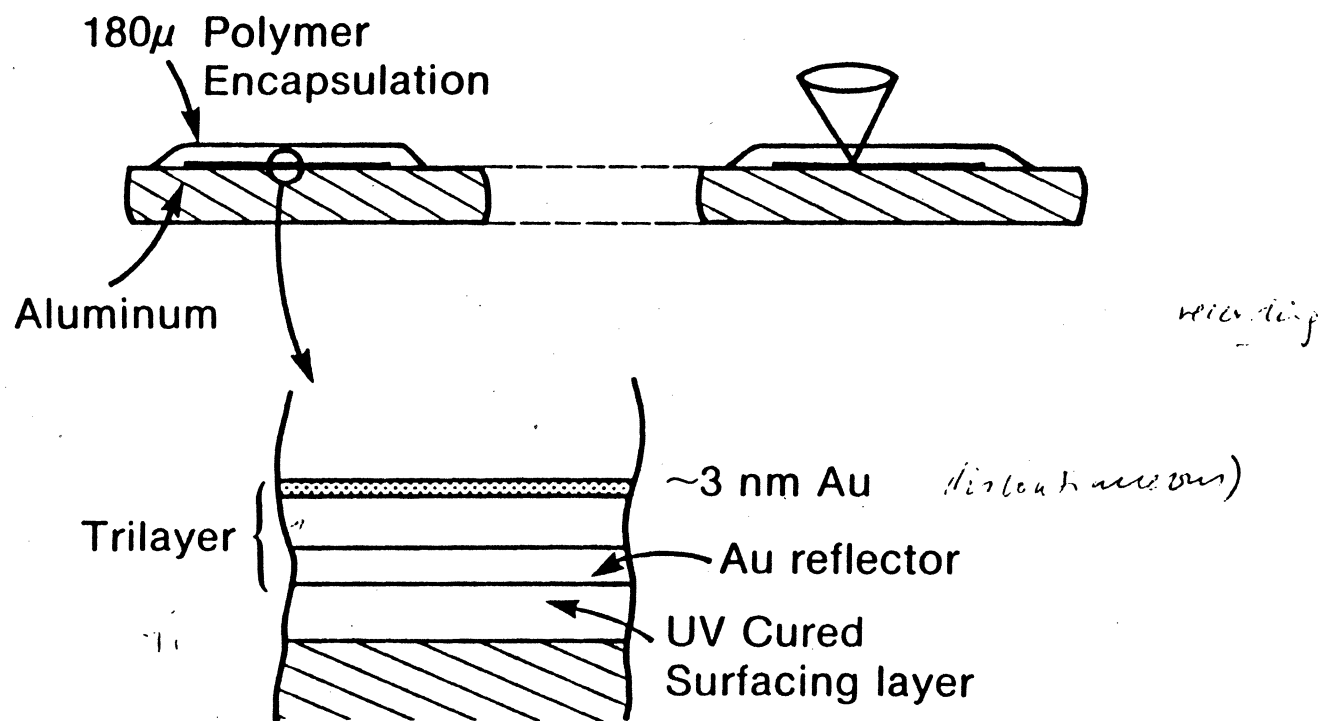
REVERSIBLE MODE

RCA, ECD
SHARP, XEROX

ALAN E. BELL
IBM



Discontinuous Gold Trilayers



TEM of Marks recorded in thin discontinuous Au (Jipson et al, IBM 1983)

Capacity (35 cm dia.)	~ 5 GB
Data Rate (1667 rpm)	3 MB/s $\lambda=633$ nm
Record Power	42 ns, 12 mW
Playback SNR	~ 34 dB (20 MHz)
Raw BER	$<10^{-5}$

E. La Budde, Burroughs (1983)

REVERSIBLE OPTICAL DATA STORAGE

- MEDIA DEVELOPMENT LAGS WRITE-ONCE BY 2-3 YRS.
- THE DEVELOPMENT OF ACCEPTABLE MEDIA COULD LEAD TO RELATIVELY RAPID INTRODUCTION OF REVERSIBLE OPTICAL STORAGE PRODUCTS
- TWO MAJOR CANDIDATES

1. MAGNETO-OPTIC

- * SONY/KDD
- * SHARP
- * N.V.PHILIPS
- * 3M (MEDIA ONLY)
- * NHK/PIONEER
- OPTIMEM
- HITACHI
- MATSUSHITA
- SANYO
- + OTHERS

2. PHASE-CHANGE

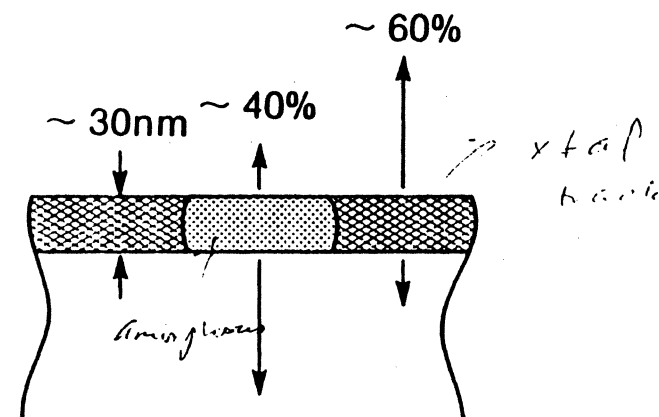
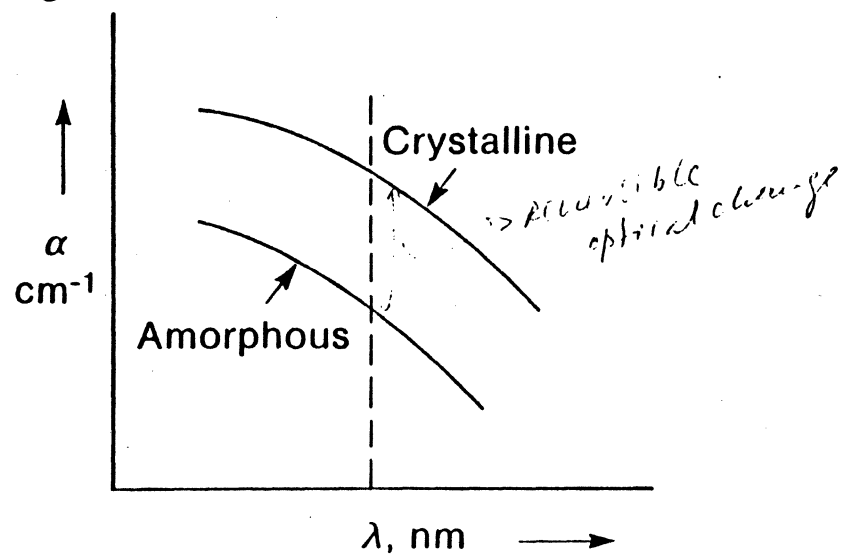
- * MATSUSHITA
- SONY
- HITACHI
- N.V.PHILIPS
- T-CSF
- + OTHERS

*invention
required*

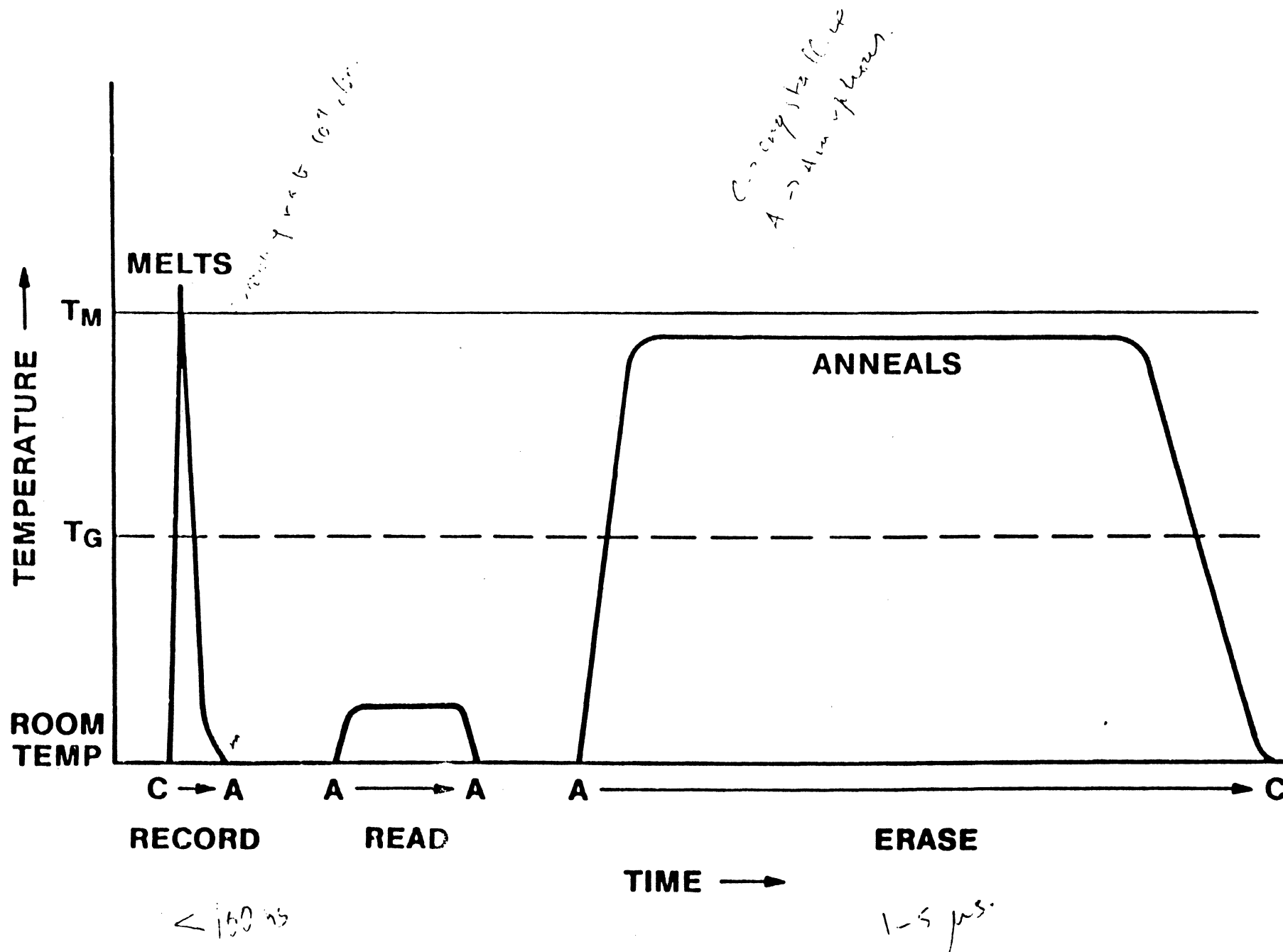
- * HAVE REPORTED ON PROTOTYPE PERFORMANCE

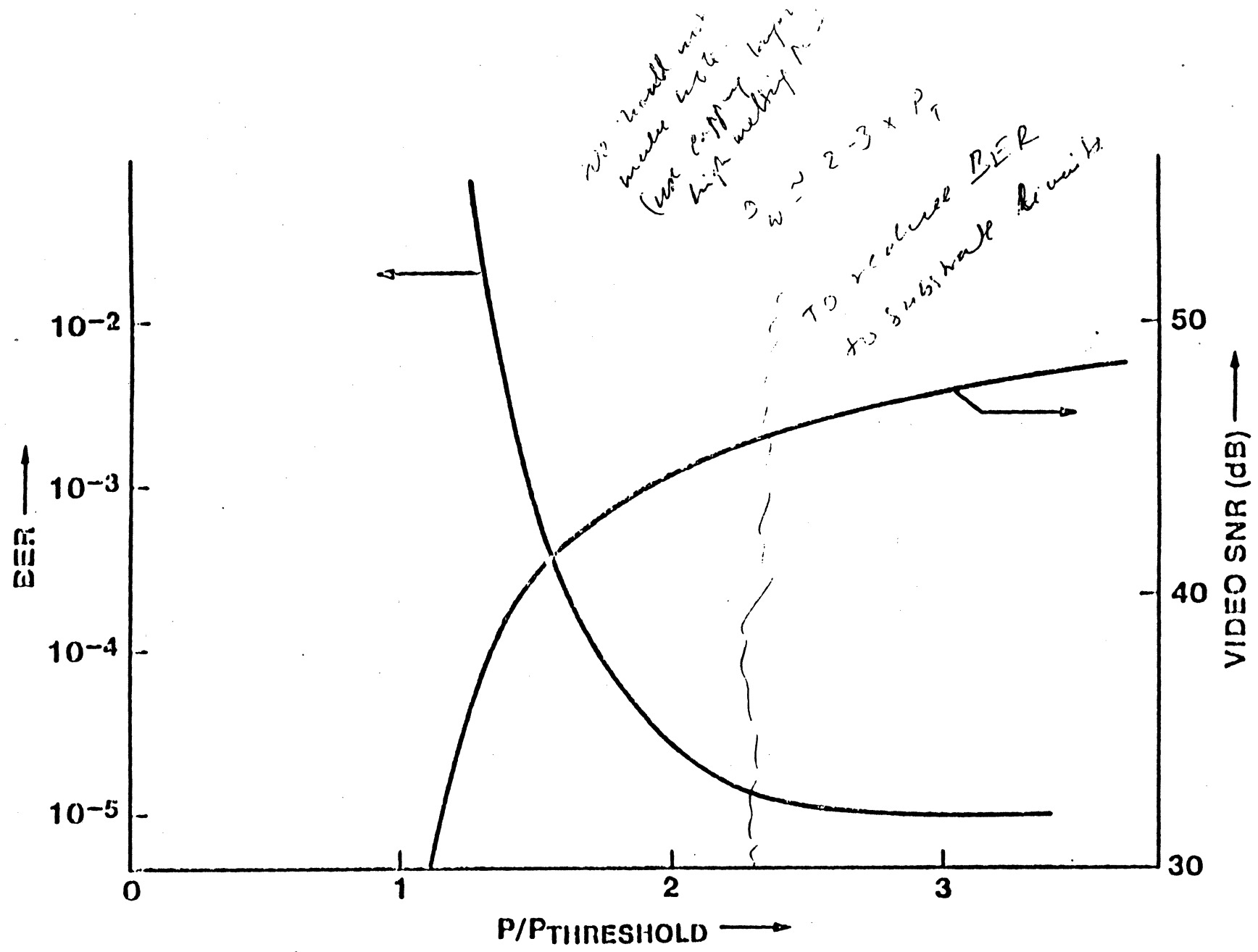
Amorphous to Crystalline Phase Change in Te-Based Materials

eg TeAsSe, TeGe, Te



Reverse-Mode Writing:
Amorphised marks along
a polycrystalline track

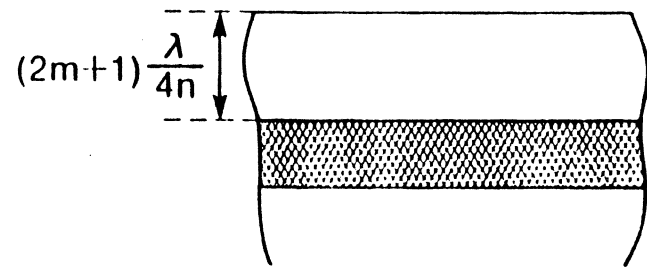




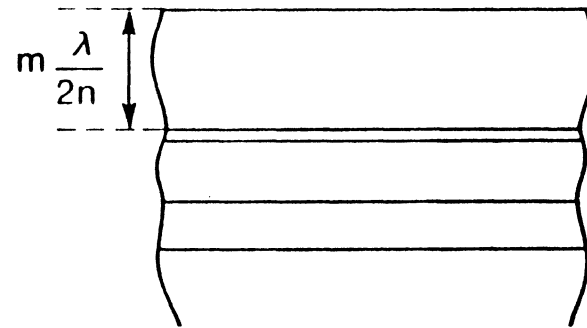
ALAN E. BELL
IBM

Capping Layers

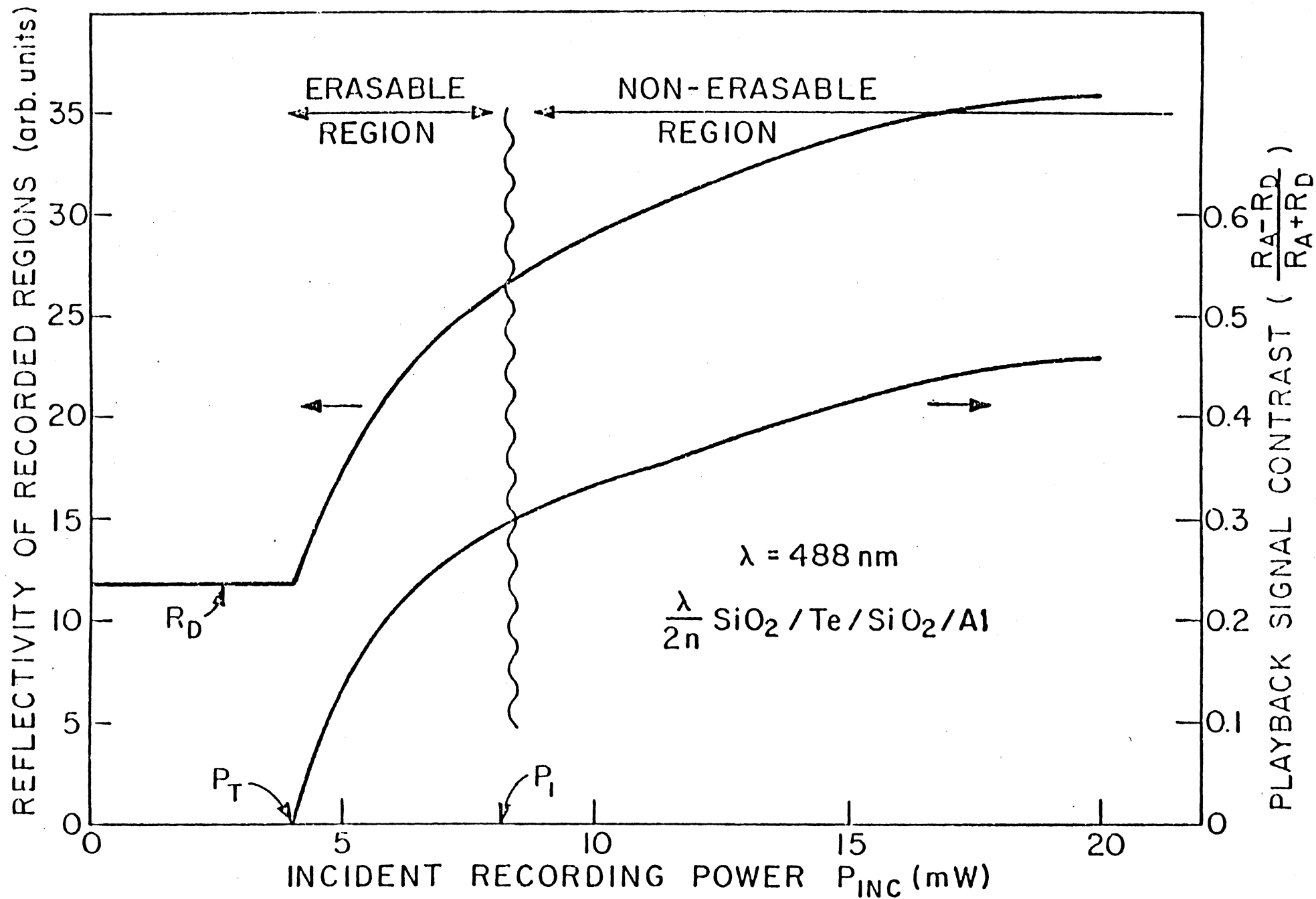
- Suppress melted hole formation
- Extend the number of write/erase cycles

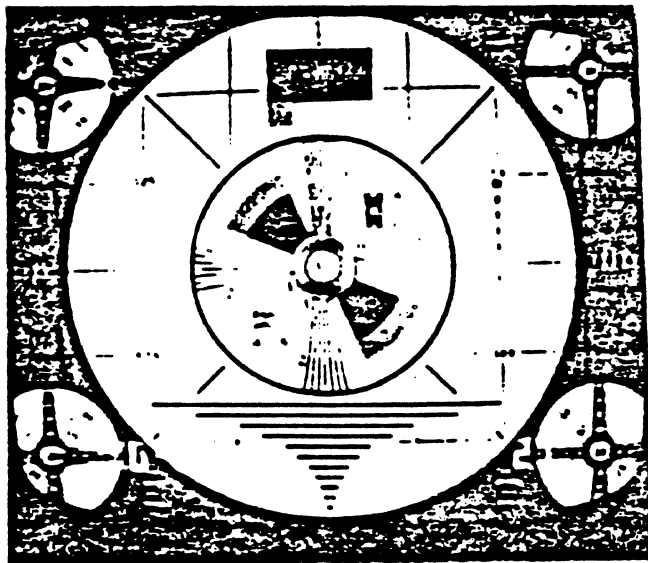


Encapsulated Unilayer

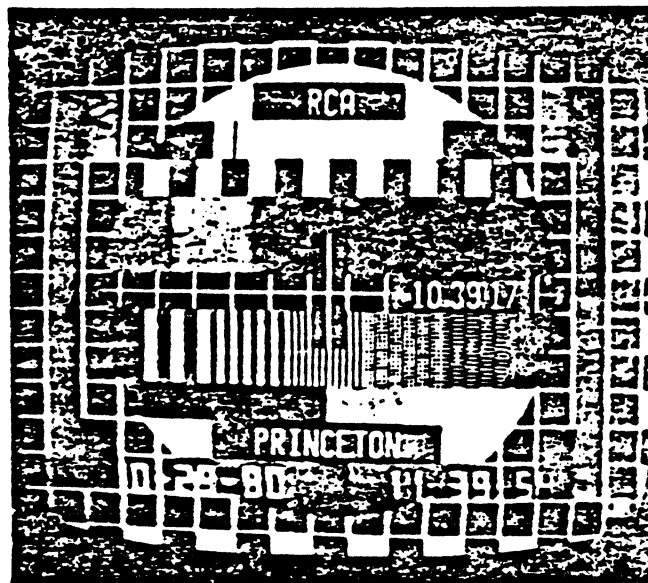


Encapsulated Trilayer

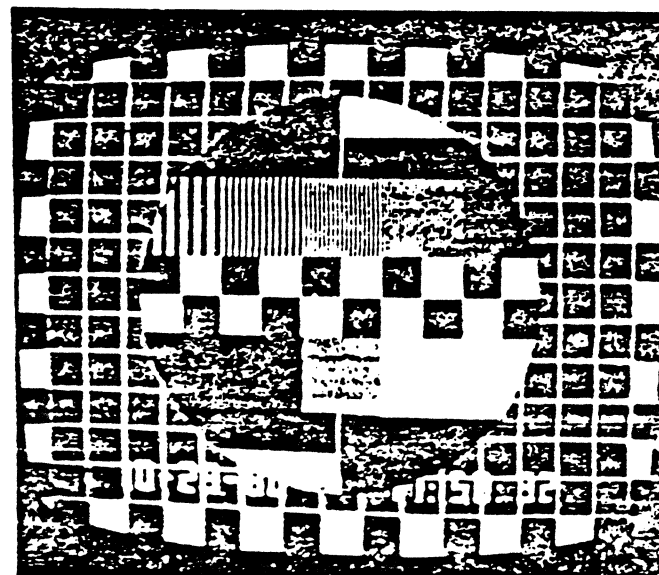




RECORDING
1



RECORDING
30



RECORDING
50

REVERSIBLE RECORDINGS OF VIDEO SIGNALS

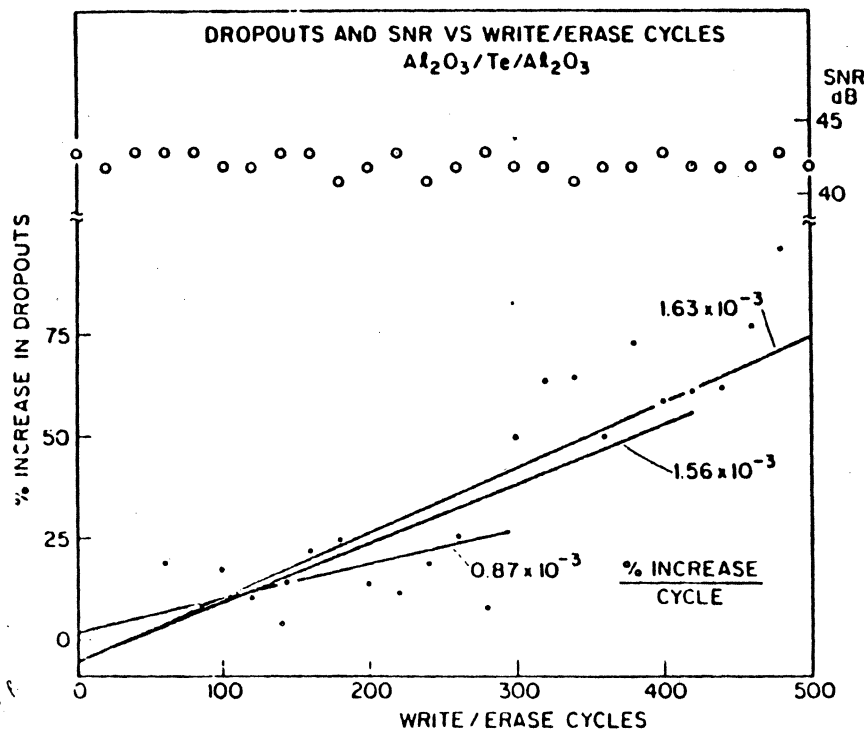
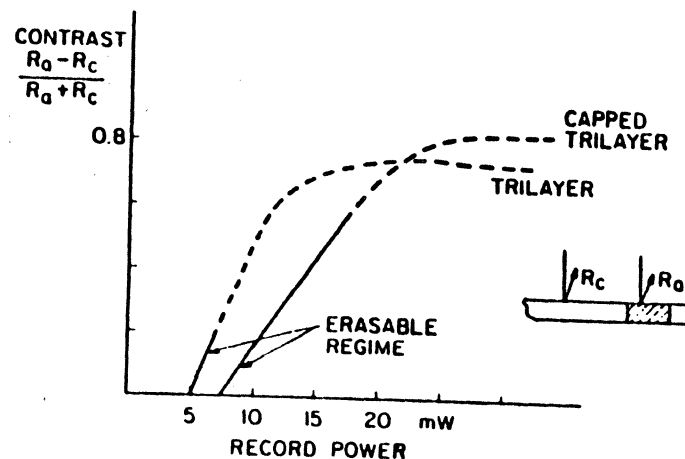
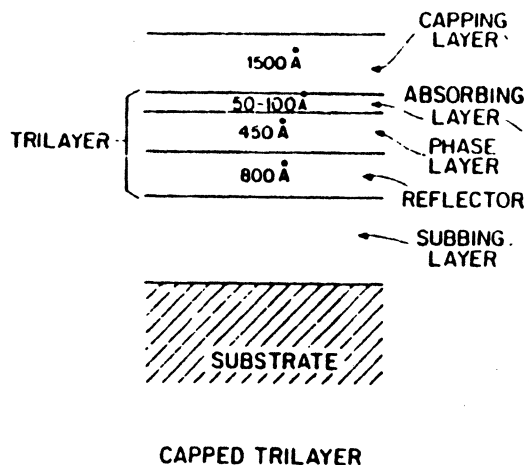


Figure 6. Dropouts and SNR for a capped Te/Al_2O_3 disc as a function of write/erase cycles using a record power of 16 mW and an erase power of 3.8 mW. The slopes were determined by linear regression assuming the test terminated at 300, 400 and 500 cycles.

Even with capping
layer the BEC increases with
cycling increases in performance
shown during cycling

AMORPHOUS TO CRYSTALLINE PHASE CHANGE

IN TELLURIUM ALLOYS

(CLEMENS, STRAND)

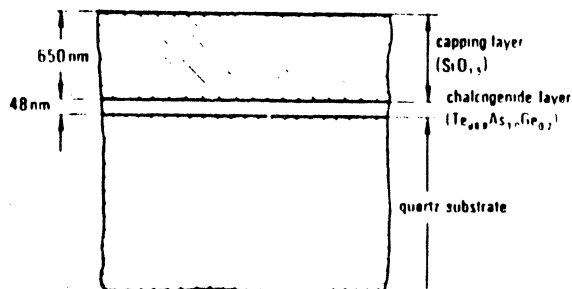
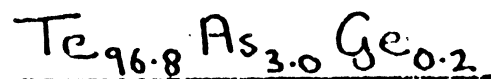


Fig. 1. Structure of the storage medium.

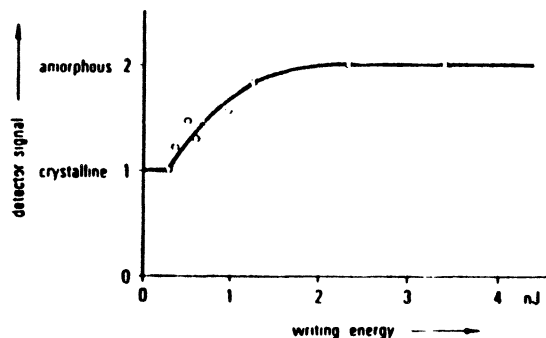


Fig. 3. Detector signal (transmission of the memory location) vs writing energy for an exposure time of 20 nsec.

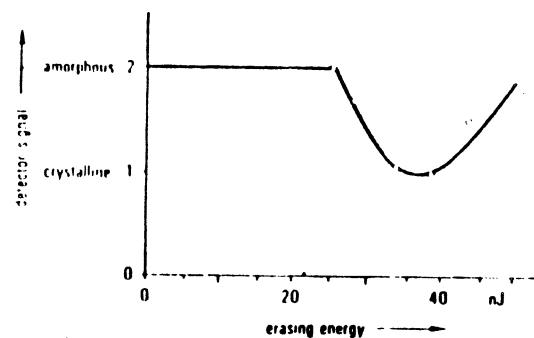


Fig. 4. Detector signal (transmission of the memory location) vs erasing energy for an exposure time of 10 μsec . At minimum signal level (reversal point at 39 nJ) complete crystallization is reached.

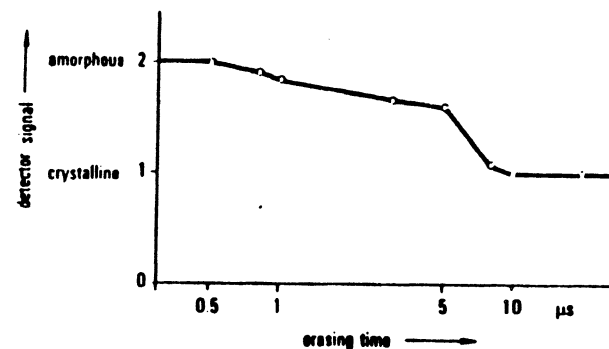


Fig. 5. Reversal points of the detector signal, i.e., maximum attainable degree of crystallization (see Fig. 4), as a function of erasing time.

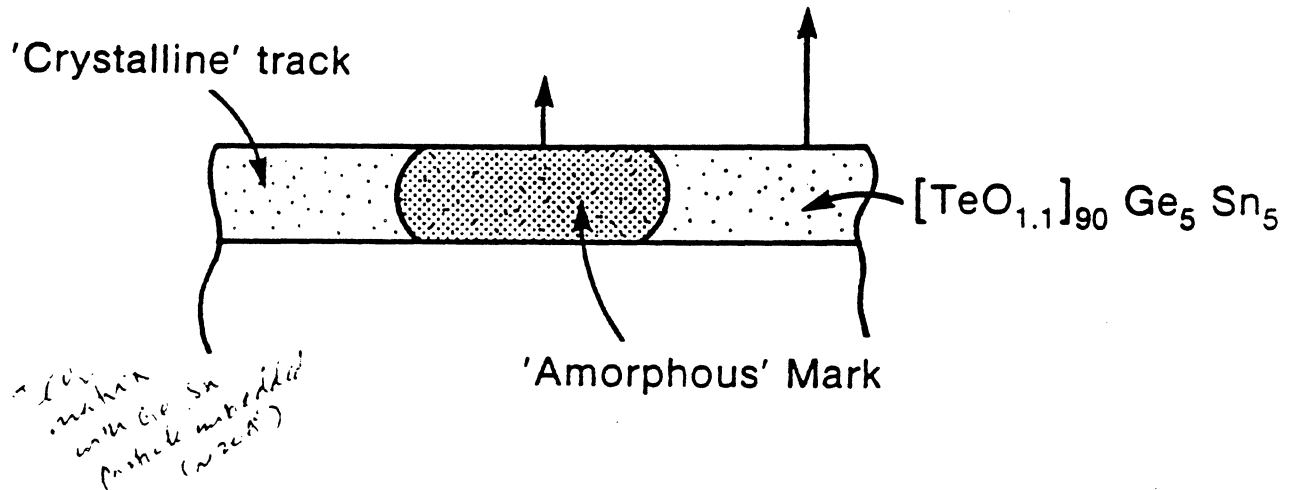
AMORPHOUS TO CRYSTALLINE PHASE CHANGE IN TELLURIUM ALLOYS

1. INCREASING THE CONCENTRATION OF ADDITIVES INCREASES THE CRYSTALLIZATION TEMPERATURE AND STABILIZES THE AMORPHOUS PHASE. THIS RESULTS IN:
 - IMPROVED DATA RETENTION LIFETIME
 - REDUCED WINDOW FOR ERASURE
2. IN HOMOGENOUS TE ALLOYS, INCREASING THE CONCENTRATION OF ADDITIVES IS ALSO ASSOCIATED WITH REDUCED CYCLABILITY.

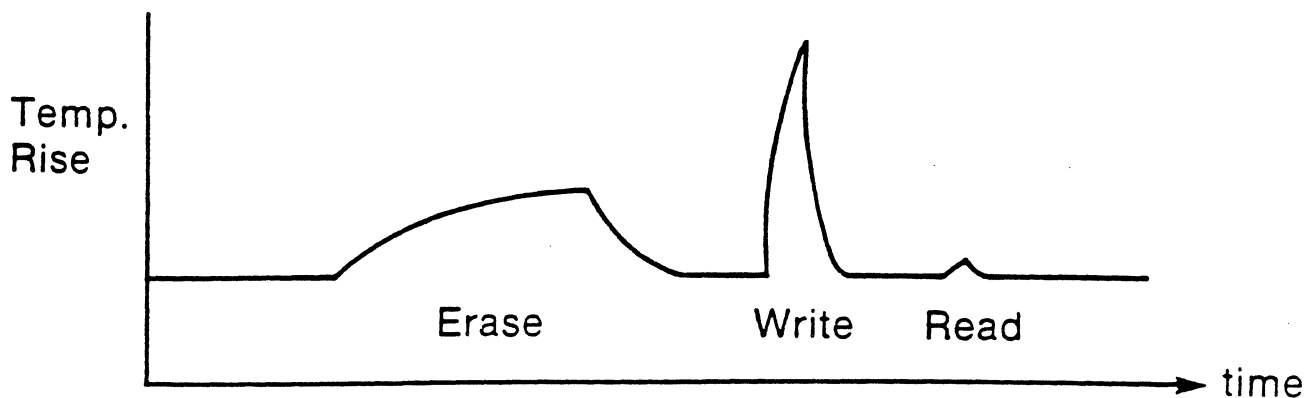
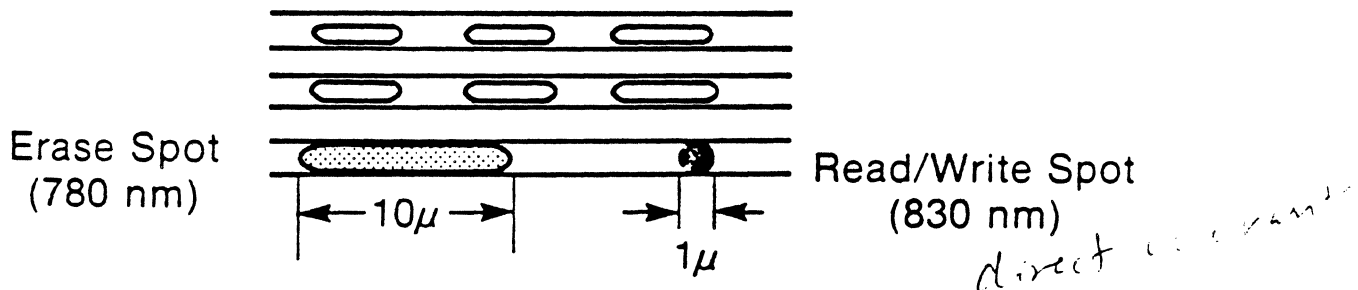
<u>MATERIAL</u>	<u>DATA RETENTION TIME</u>	<u>NUMBER OF CYCLES</u>
TE	MINUTES	-
TE ₉₈ AS _{1.9} GE _{0.1}	HOURS	-
TE _{96.8} AS _{3.0} GE _{0.2}	WEEKS	4 10 ⁴
TE ₈₀ GE ₂₀	STABLE	~10 ² - 10 ³
TE ₈₈ AS ₅ GE ₇	STABLE	~20

Reversible Phase-Change Media

- 'Amorphous' to 'Crystalline' transition in Tellurium Suboxide with Ge and Sn additives



- Recording/Erasing Process



Takenaga et al (1983) Matsusnita

Matsushita 2-beam Head for Reversible Phase-change Media

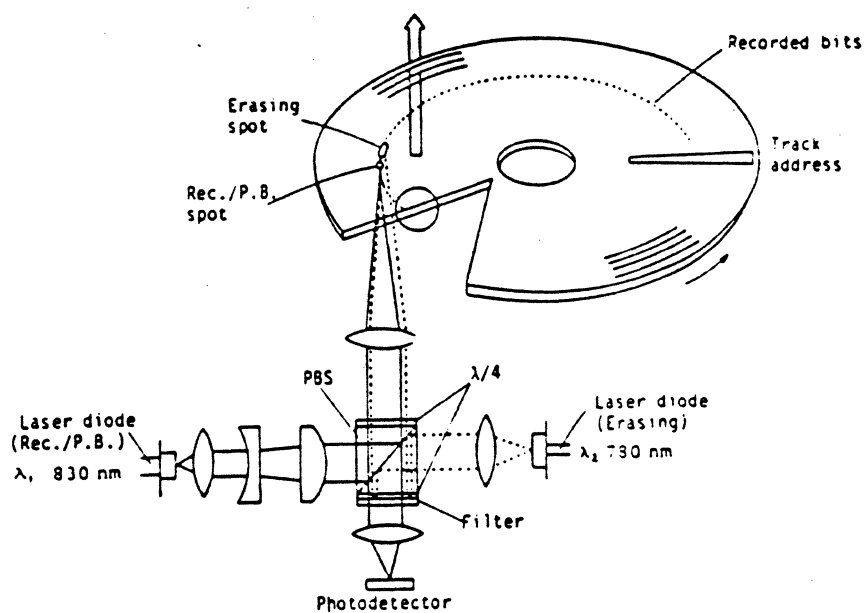
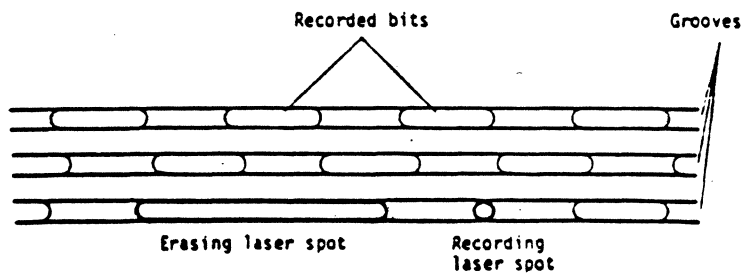
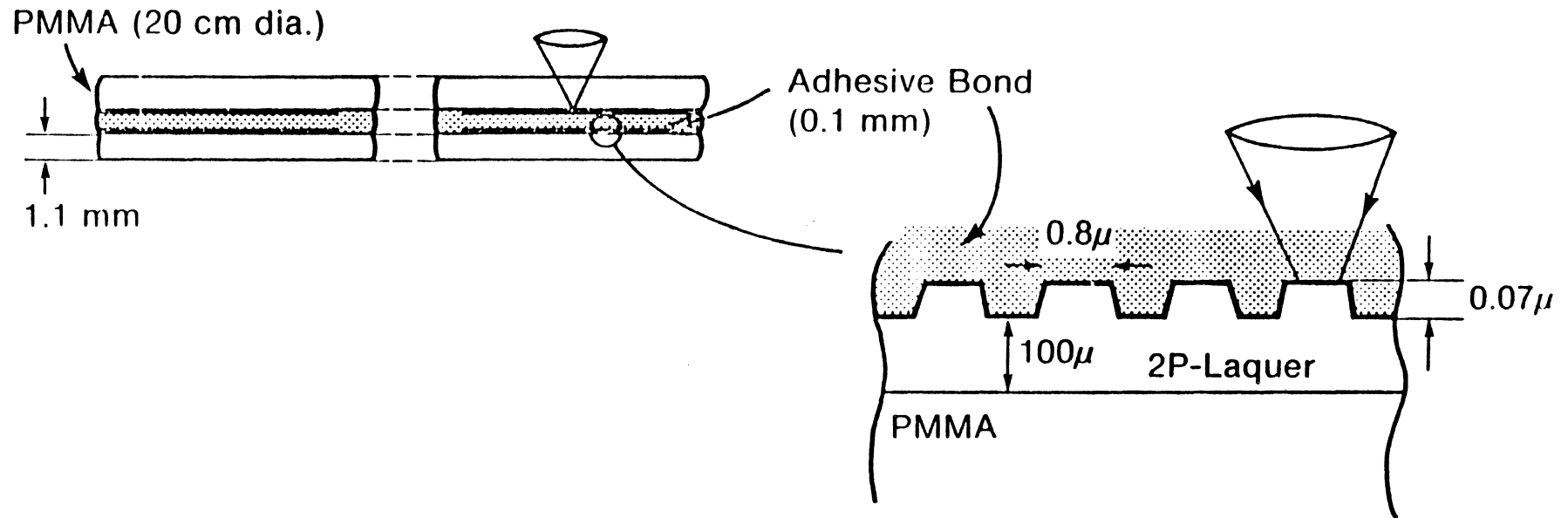


Figure 1 Basic construction of an erasable disc and optical head.



Reversible Phase-Change Disk Characteristics (Matsushita)



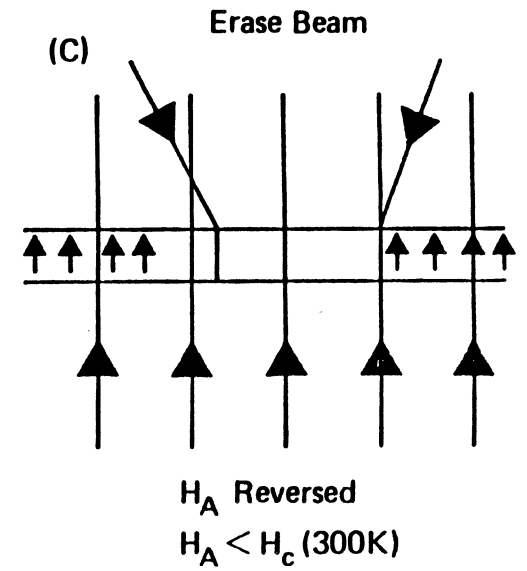
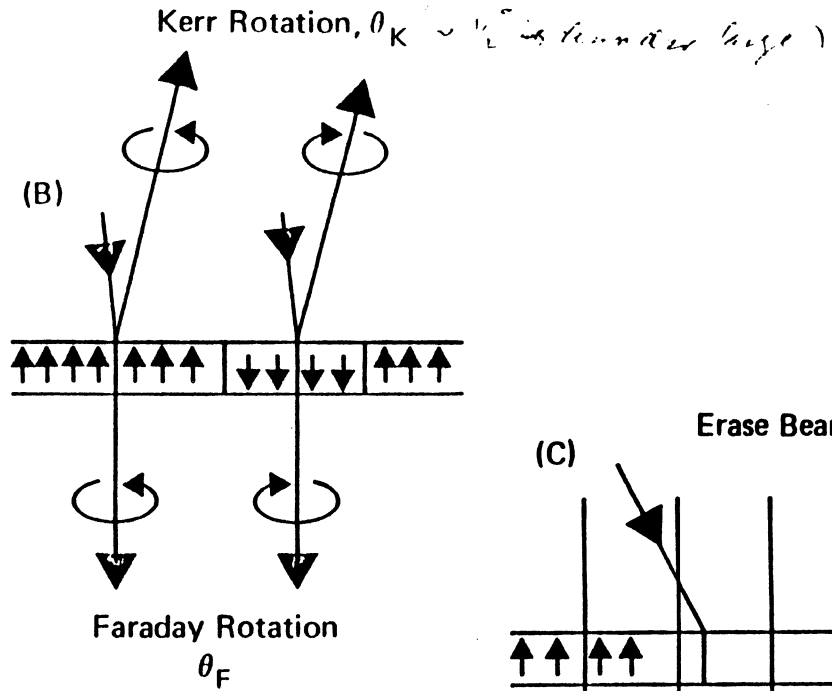
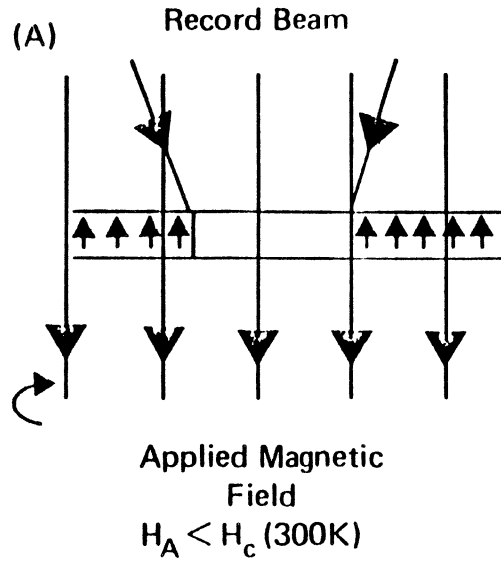
Data Rate	10 Mb/s	(1800 rpm)
Record Power	8 mW	(6mW/μ ²)
Erase Power	10 mW	(0.7 mW/μ ²)
Playback SNR	55 dB	(30 kHz)
Cycles	>10 ⁶	

Takenaga et al (1983)

PHASE CHANGE MEDIA

- Te-based media are the leading candidates
- Write sensitivity is adequate
- Signal levels are high
- Multilayer structures are required to inhibit ablation ** key problem*
- Cyclability $\geq 10^6$ has been demonstrated
- Direct overwrite is possible ** key advantage*
- A purely thermal process demands a trade-off between data retention and ease of erasure
- Media stability not yet proven

Magneto-Optic Recording, Reading and Erasing



Shot-Noise Limited SNR

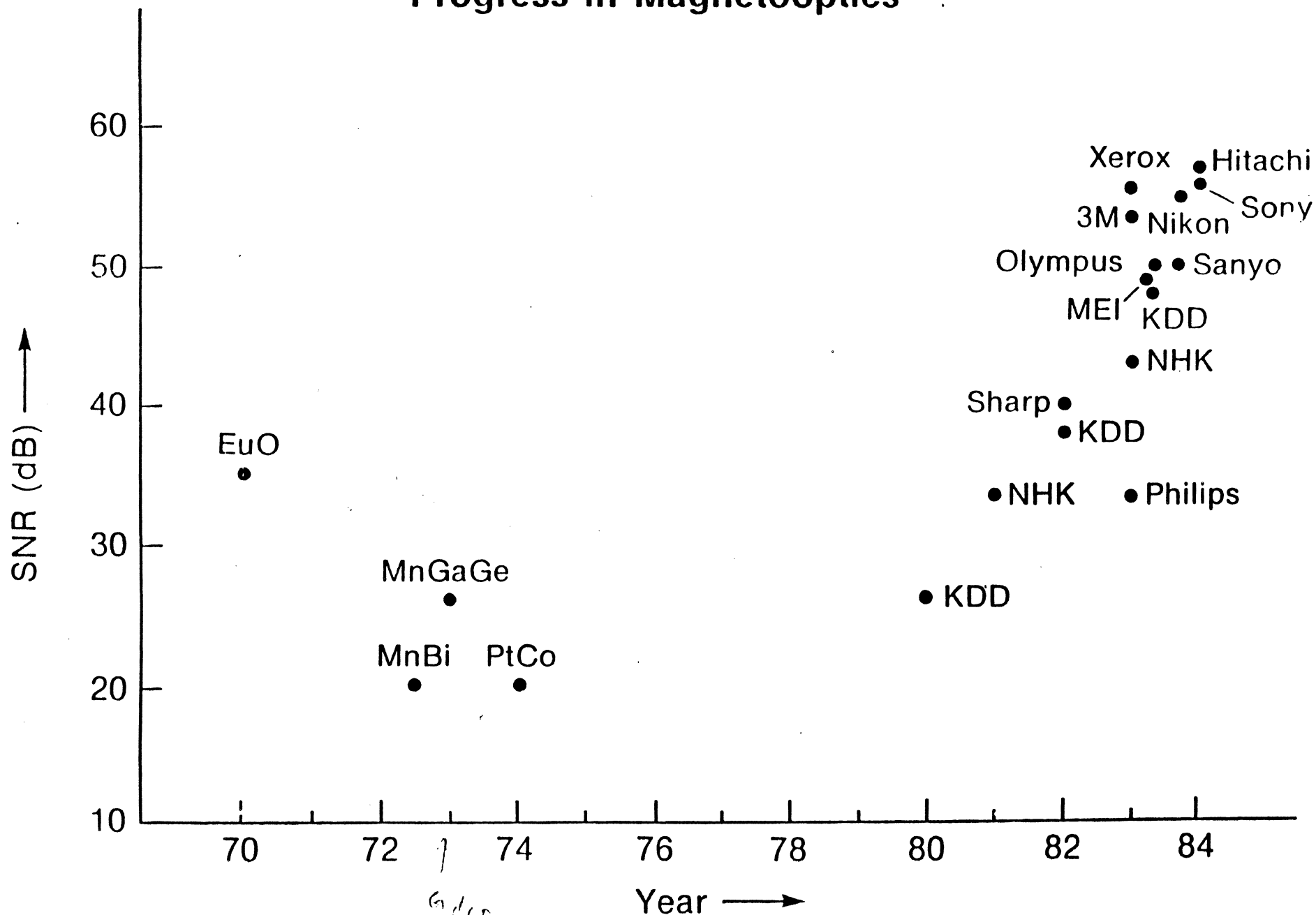
$$\text{SNR} \propto \left(\frac{P_R}{B} \right)^{1/2} R^{1/2} \theta_K$$

difficult to
understand.
It takes about 30 min
to read.

MAGNETO-OPTIC MEDIA

- **< 1973:** Early Candidates, eg MnBi, EuO,
Found to be Impractical
- **1973:** IBM Workers Propose GdCo
Amorphous
Reasonable Kerr Rotation
Micron-Sized Bits Unstable
- **1975-1984:** Rare Earth/Transition Metal
Properties are Investigated and
Compositions Refined
eg TbFe Increased Coercivity
TbFeCo Increased Kerr Rotation
- **1981-1984:** Interference Structures Utilized
To Enhance Kerr Rotation
- **1982-1984:** Several Reports of Practical
Performance Levels with Research
Prototype Drives

Progress in Magneto-optics

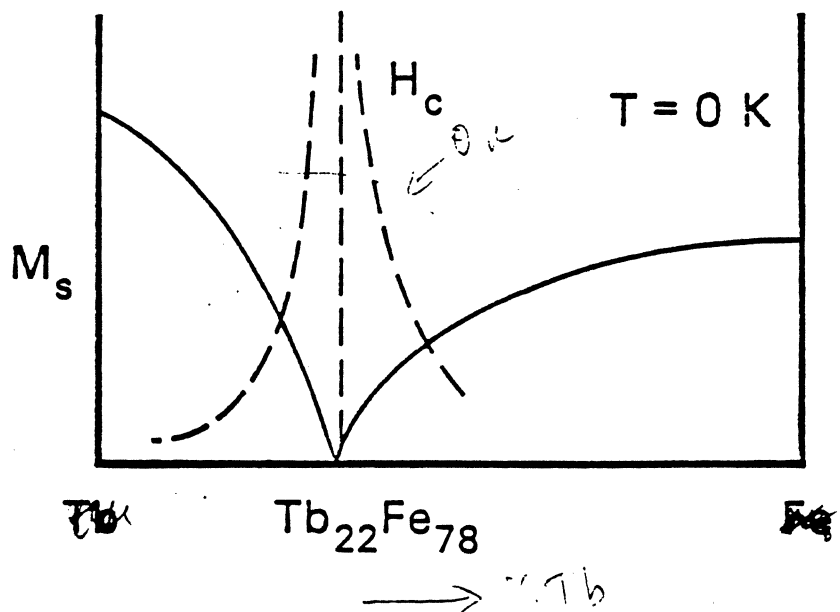
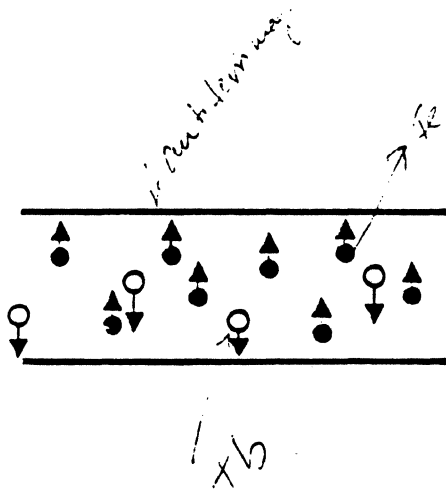


Advantages of RE-TM Alloys

- Amorphous
- Ferrimagnetic
- Good Kerr rotation
- Moderate Curie temperatures

$$M \sim M_{Fe} - M_{Tb}$$

$$\theta_K \sim M_{Fe}$$

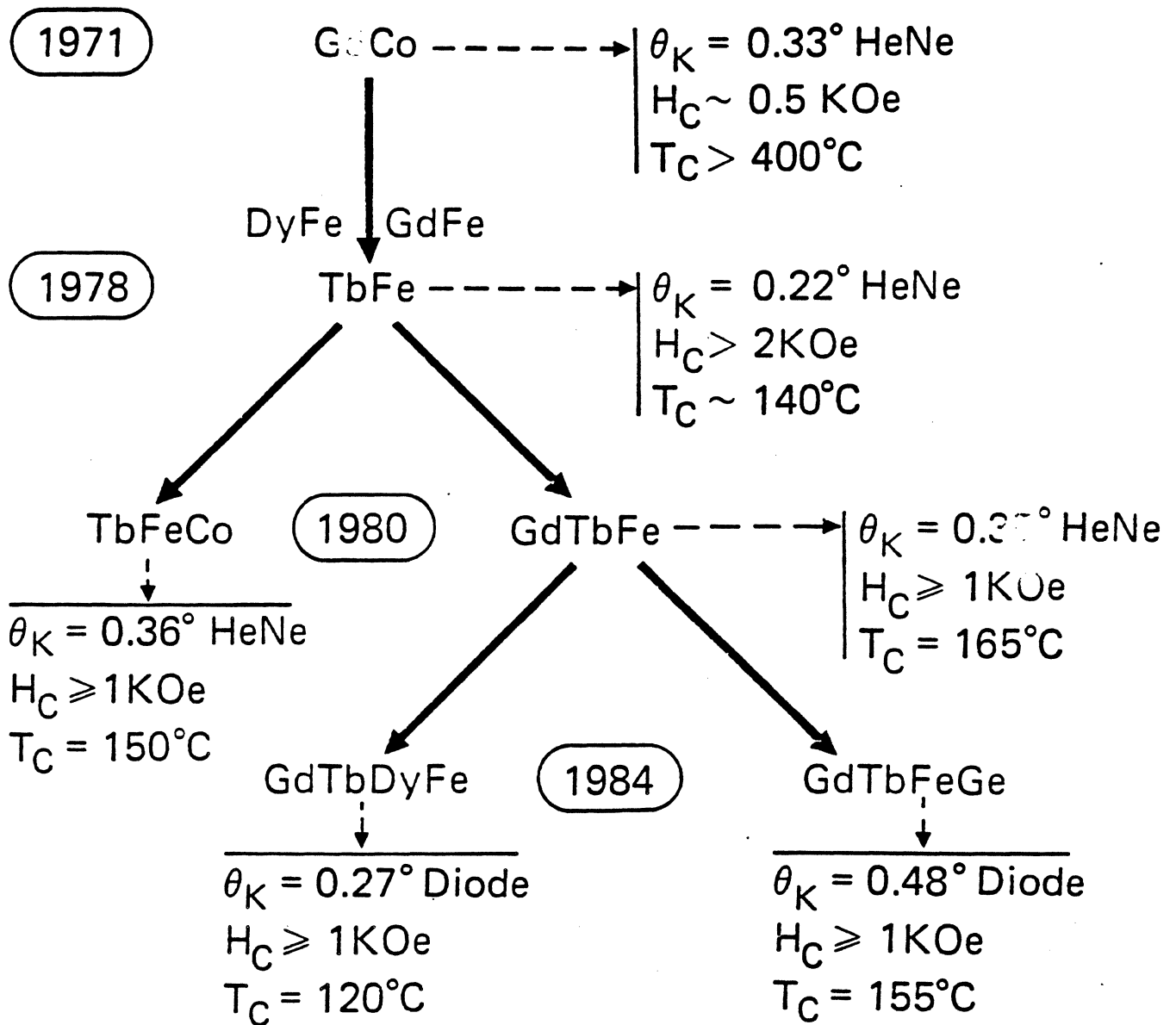


For Perpendicular Magnetization

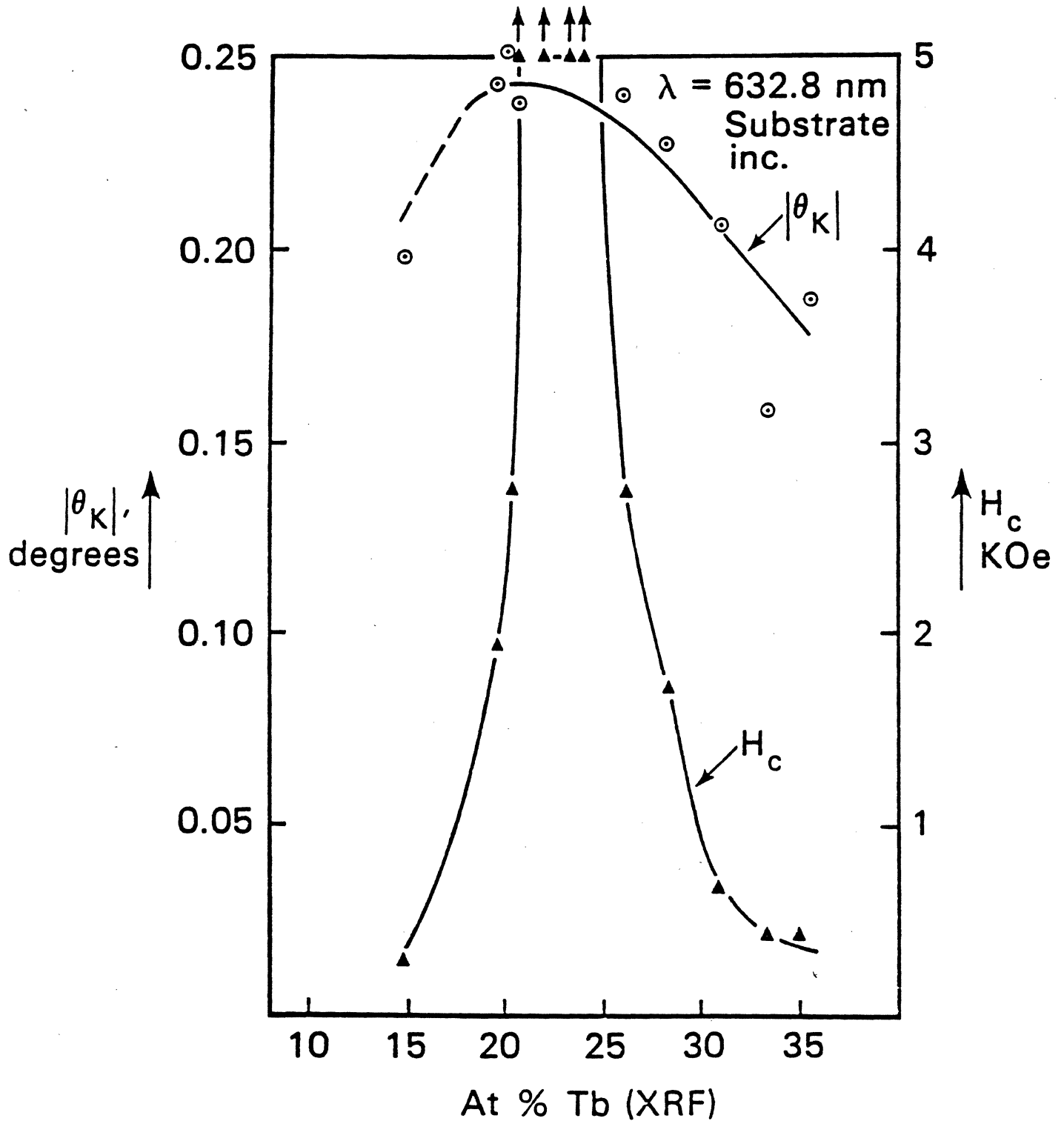
$$K_{\mu} > 2\pi M_s^2$$

magnetostatic energy

Evolution of RE-TM Alloys for M - O Storage



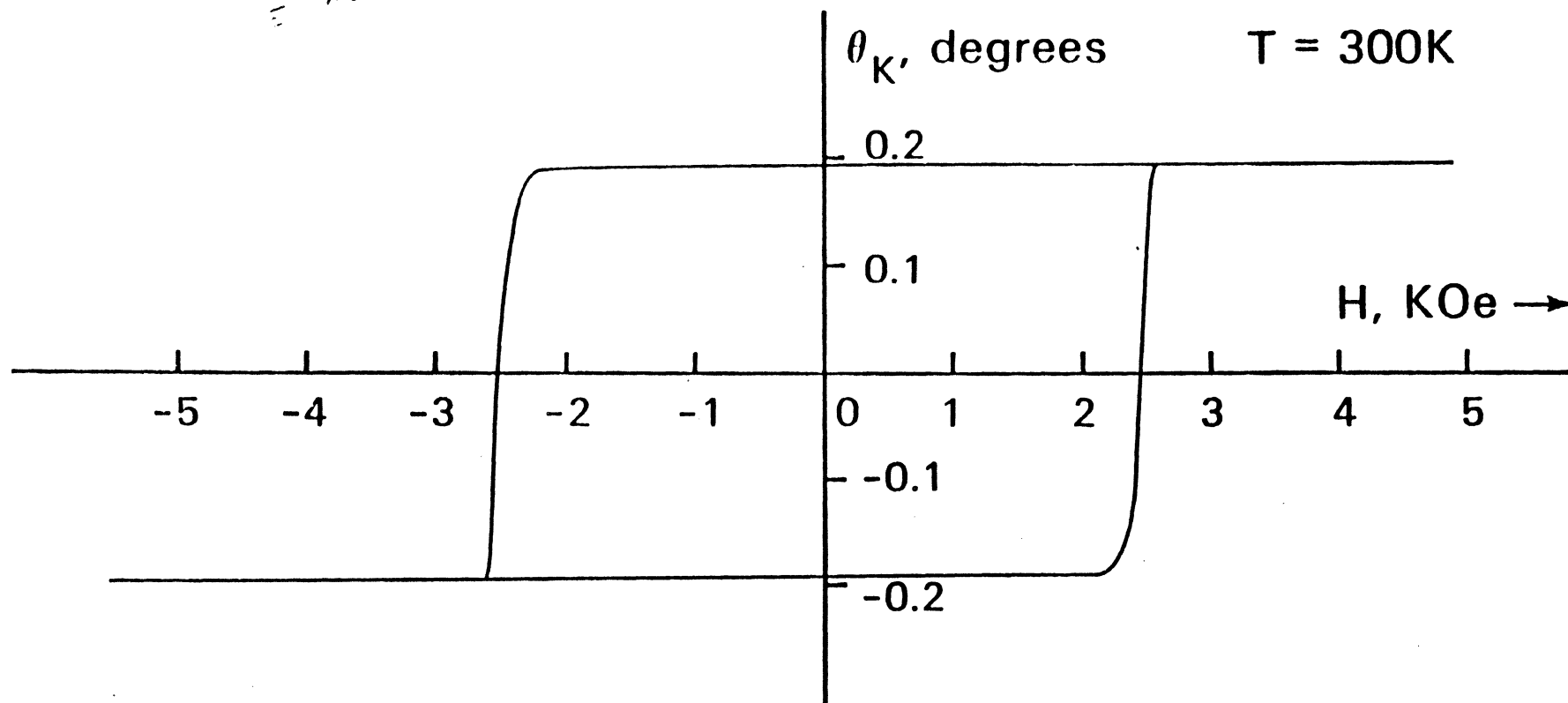
Magneto-Optic Properties of $\text{Tb}_x\text{Fe}_{1-x}$ Alloys (IBM)



$\theta_K - H$ loop
 $\equiv$ M-H loop

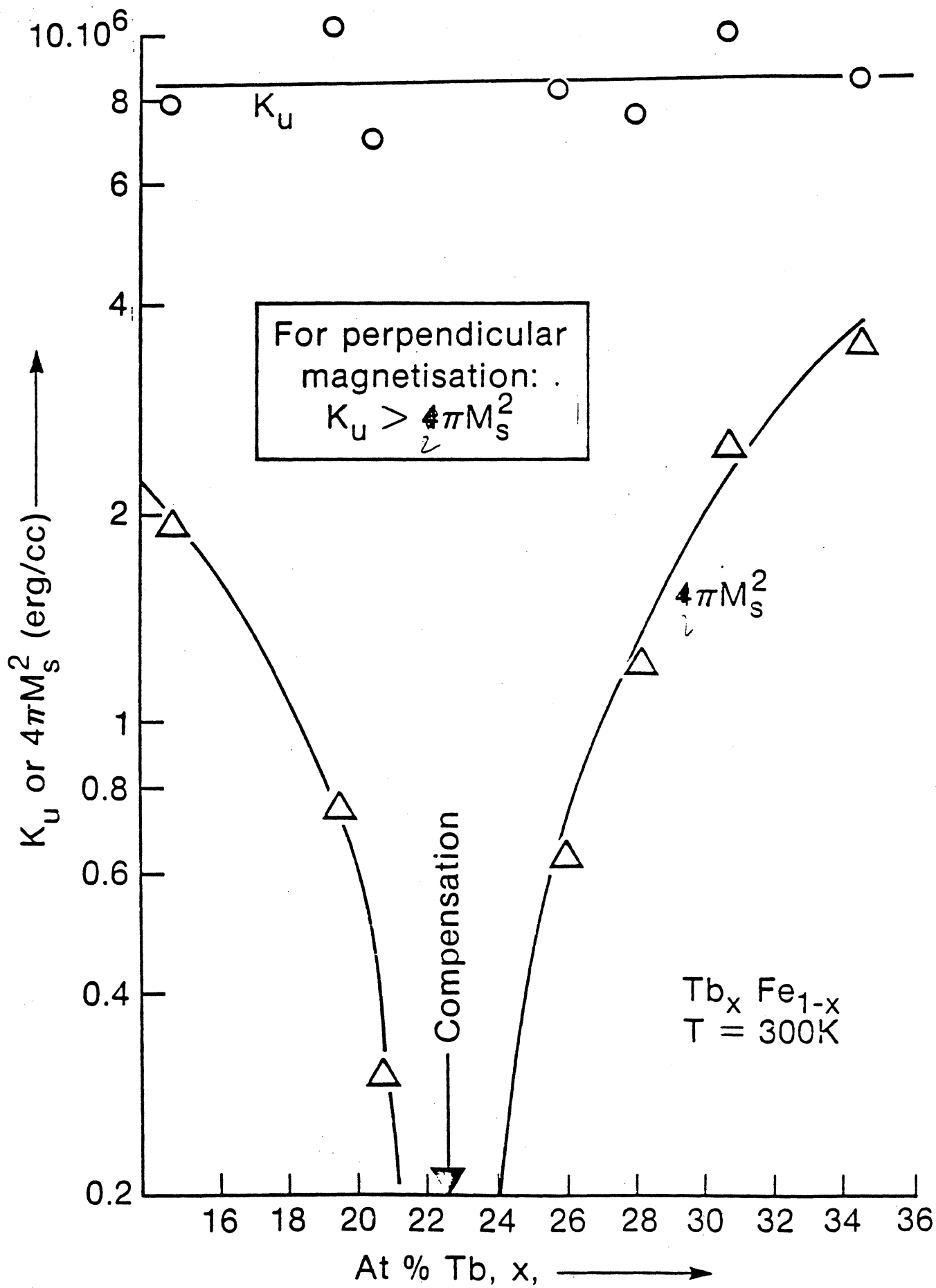
Tb₁₉Fe₈₁

T = 300K

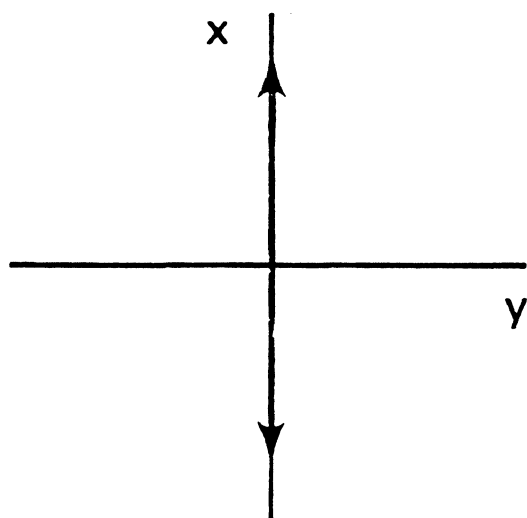


$$\theta_K = 0.21^\circ$$

$$H_c = 2500 \text{ Oe}$$

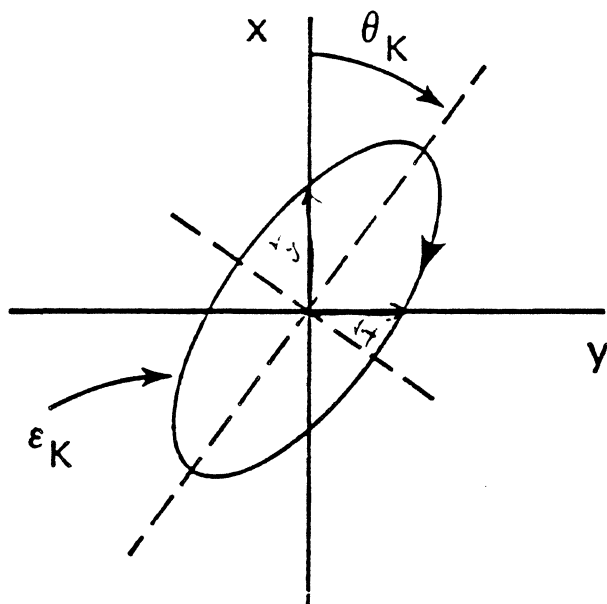


Magneto-Optic Read-Out



Incident:

Plane polarized



Reflected:

Elliptically polarized

$$\tilde{r}_x = r_x e^{i\delta_x}$$

$$\tilde{r}_y = r_y e^{i\delta_y}$$

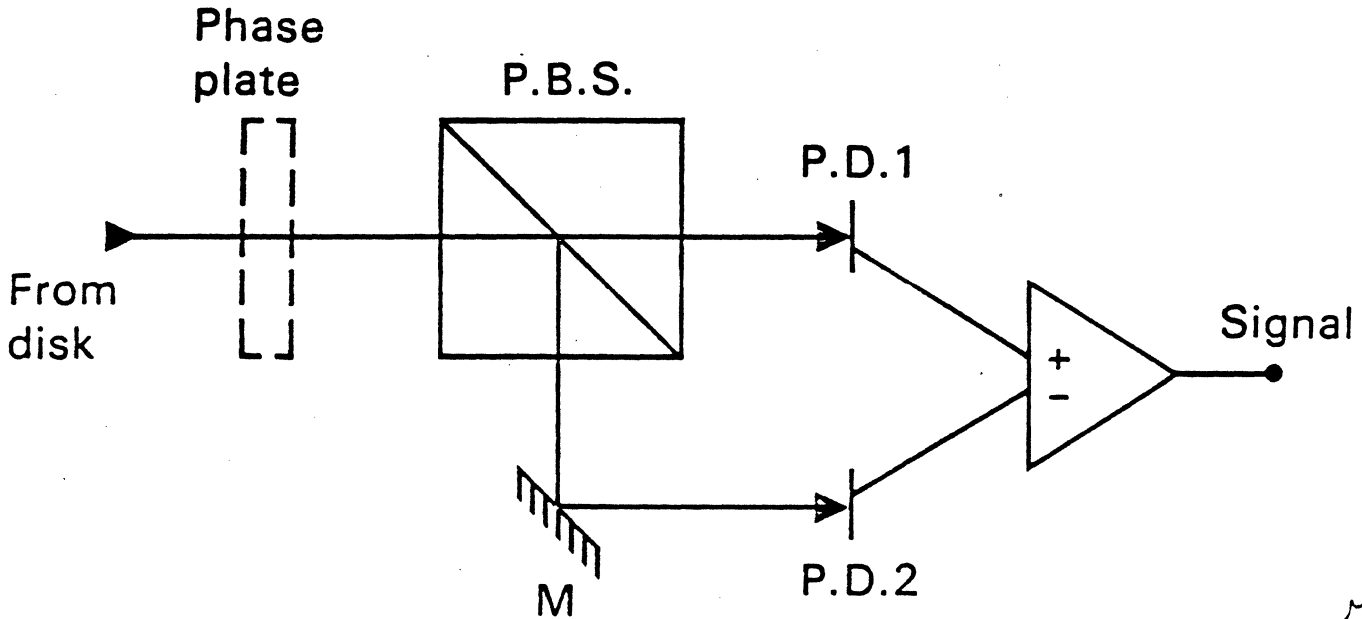
$$r_y \ll r_x \quad \left[\frac{r_y}{r_x} \ll 1 \right]$$

$$\delta = \delta_y - \delta_x$$

(magneto-optic effect)
normal reflection

Magneto-Optic Detection

- Differential detection maximizes SNR



Shot-noise limited

$$\text{SNR} \propto I^{1/2} \frac{r_x r_y \cos \delta}{(r_x^2 + r_y^2)^{1/2}}$$

Physical
limit

r_y - magneto-optic effect.
Phase difference in r_x & r_y .

$$\text{SNR} \propto I^{1/2} \frac{r_x r_y}{r_y} = (I r_x)^{1/2} \theta_k$$

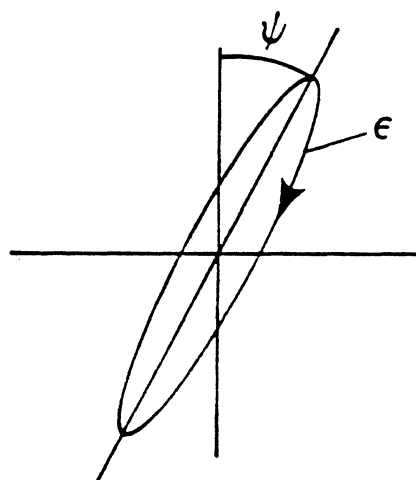
$$= I^{1/2} r_y$$

$$\tan \theta_k = \theta_k = \frac{r_y}{r_x}$$

$$\theta_k = \left(\frac{r_y^2}{r_x^2} \right)^{1/2}$$

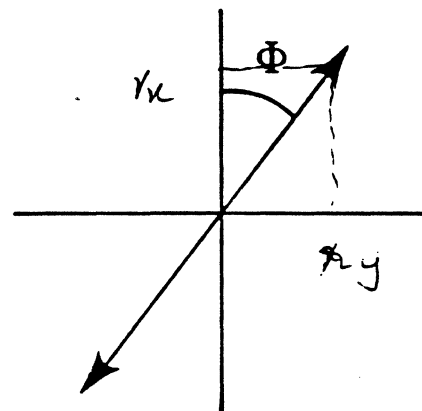
Use of Phase Plate

Introduce Phase Compensation = $-\delta$



Elliptical and Rotated

With
→
Compensation



Pure Plane Polarised
Additional Rotation

$$\Phi = (\psi^2 + \epsilon^2)^{1/2} \quad \text{If } \epsilon, \psi \text{ are small}$$

When $\delta = 0$

$$\text{SNR} \propto \left(\frac{I_p}{B} \right)^{1/2} r_y \quad (r_y \ll r_x)$$

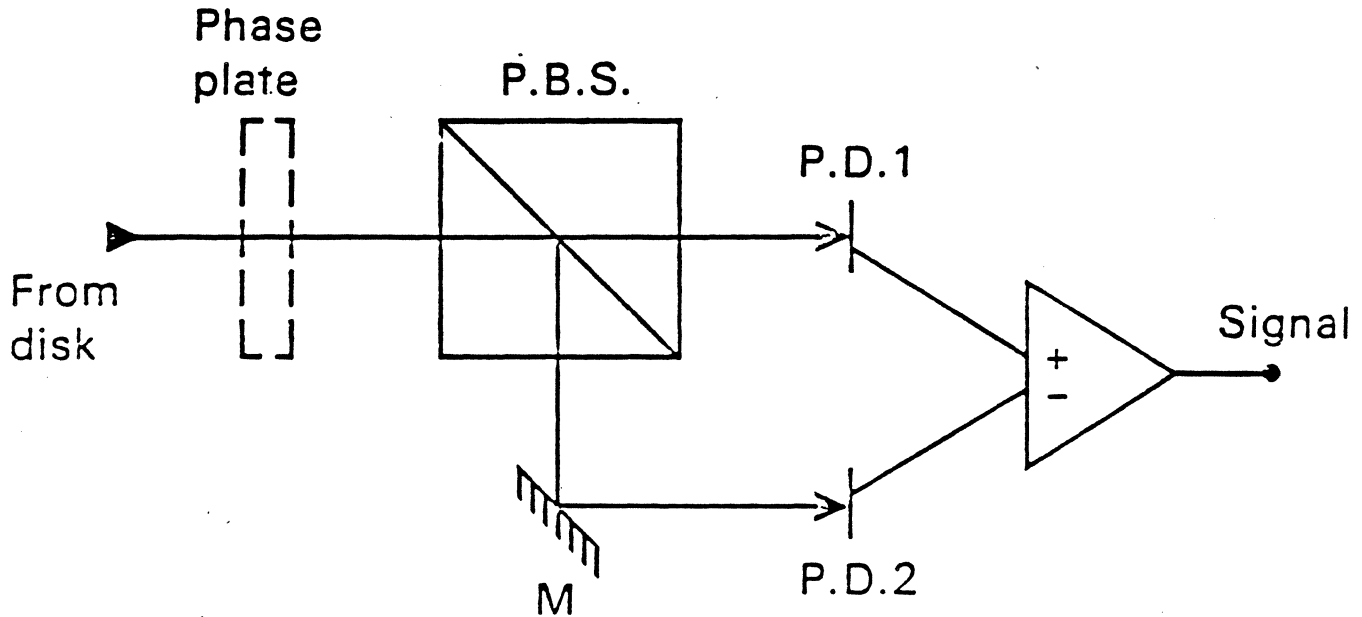
$$\propto \int_f^{1/2} r_x \frac{r_y}{r_x}$$

$$\propto \int_f^{1/2} L^{1/2} \delta r$$

fig. 9.10

Magneto-Optic Detection

- Differential detection maximizes SNR



SIGNAL

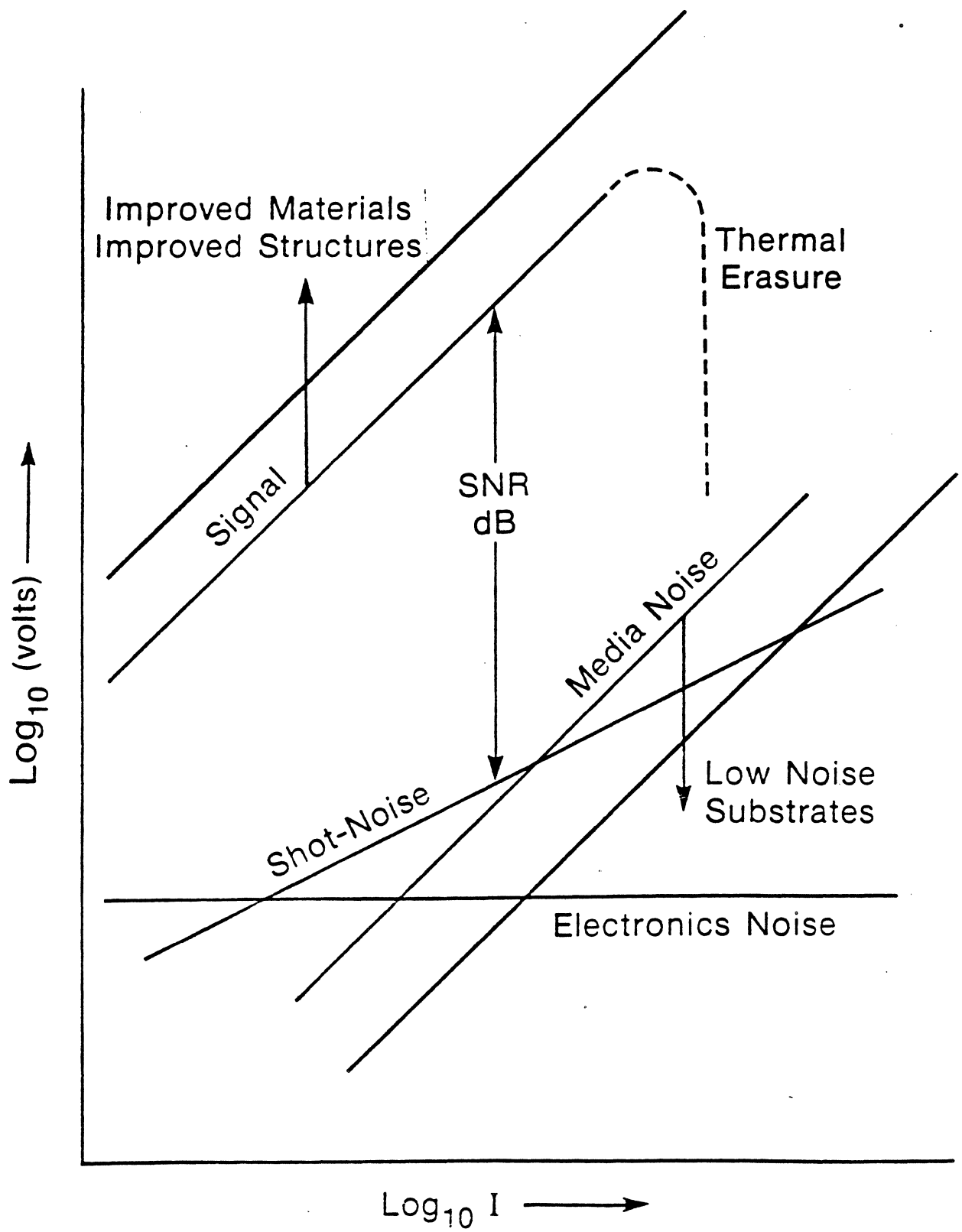
$$\propto IR\Theta_k$$

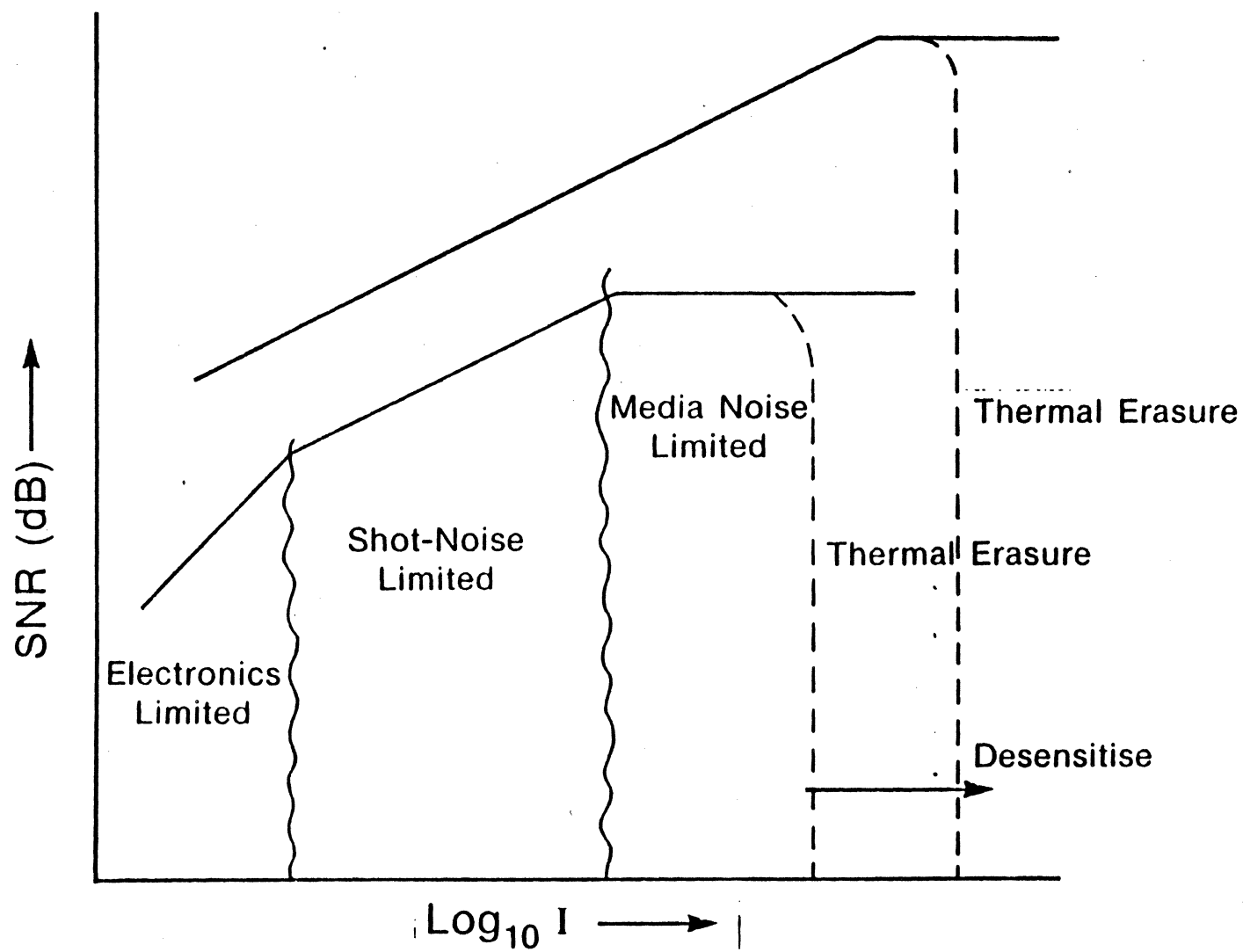
NOISE/ (Hz)^{1/2}

$$\propto (IR)^{1/2} \quad \text{Shot Noise}$$

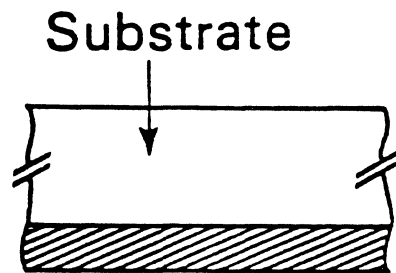
$$+ (IR)^\epsilon \quad \text{Media Noise}$$

$$+ \text{Const.} \quad \text{Electronics Noise}$$

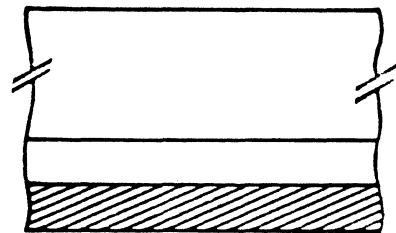




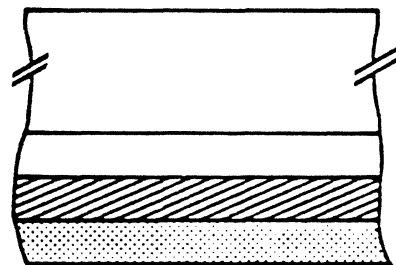
Coating Structures for Magneto-Optic Media



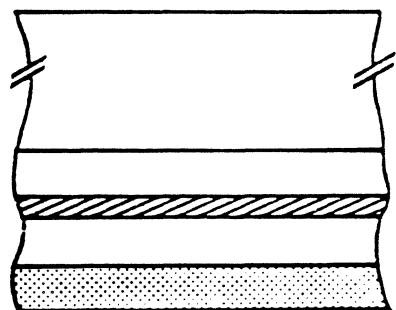
Single Layer



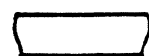
Dielectric Enhanced
Single Layer



Dielectric Enhanced
Bilayer



Dielectric Enhanced
Trilayer



Dielectric Material

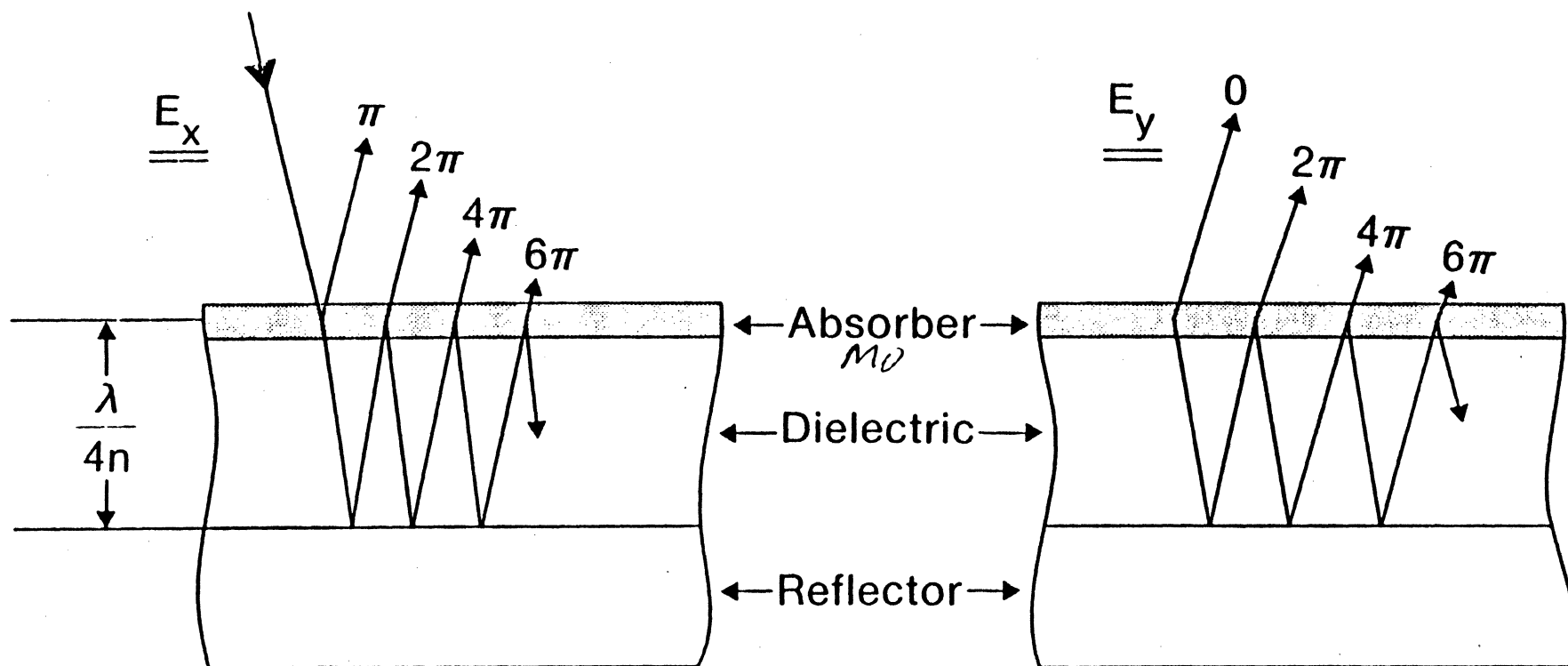


M-O Media



Reflector Material

Magneto-optic Anti-reflection Trilayer



Destructive Interference

$$\tilde{r}_x \rightarrow 0$$

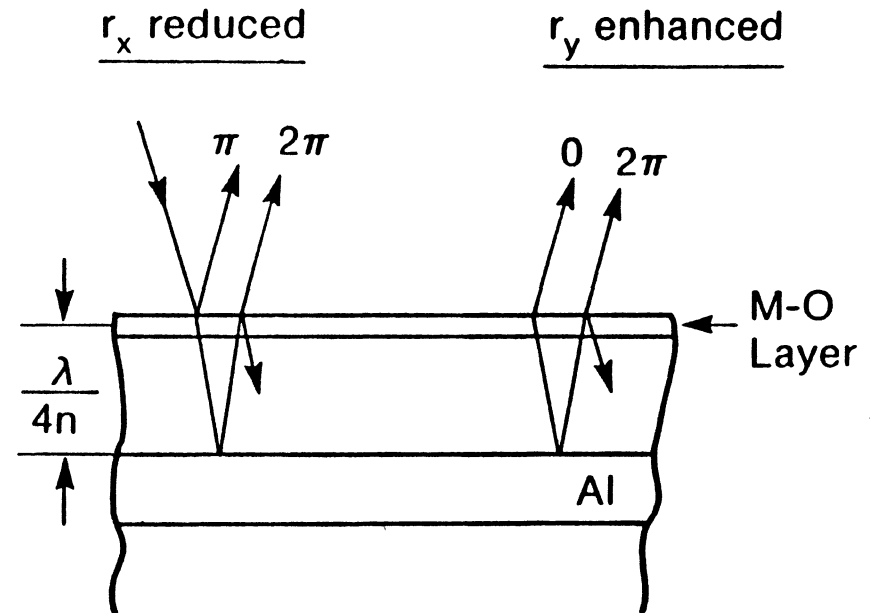
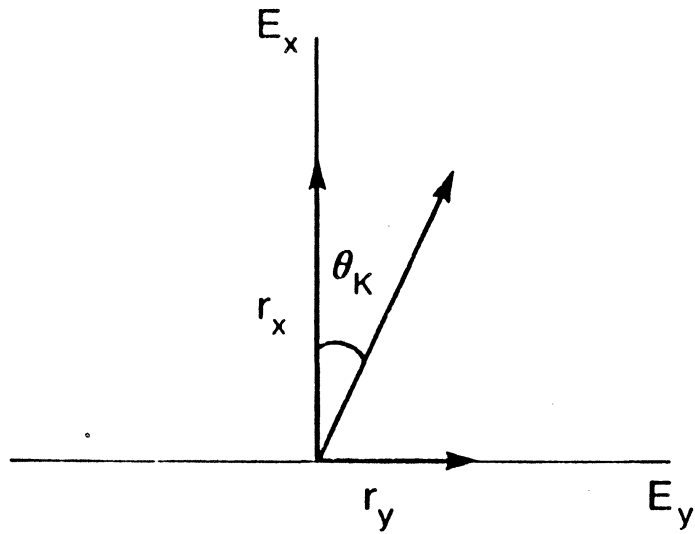
High Absorption of
Record-Beam Energy

Constructive Interference

$\tilde{r}_y$ Enhanced

Increased Playback SNR

Enhancement of Kerr Rotation



	θ_K°
Single layer	0.27
Bilayer	0.5
Trilayer	0.75
Quadrilayer	1.7

GdTbFe, $\lambda = 800$ nm
Ohta et al, Sharp (1983)

ANALYSIS OF MAGNETO-OPTIC MEDIA

- Normal modes of propagation are RH and LH circularly polarized light

$$\tilde{n}_+ = (\epsilon_{xx} + i\epsilon_{xy})^{1/2} = n_- - ik_+$$

$$\tilde{n}_- = (\epsilon_{xx} - i\epsilon_{xy})^{1/2} = n_- - ik_-$$

- Resolve plane polarized read beam into equal components of RH and LH polarized light
- Compute complex reflectance for RH and LH polarized components

$$\tilde{r}_+ = r_+ e^{i\delta_+} \quad \tilde{r}_- = r_- e^{i\delta_-}$$

- Recombine solutions

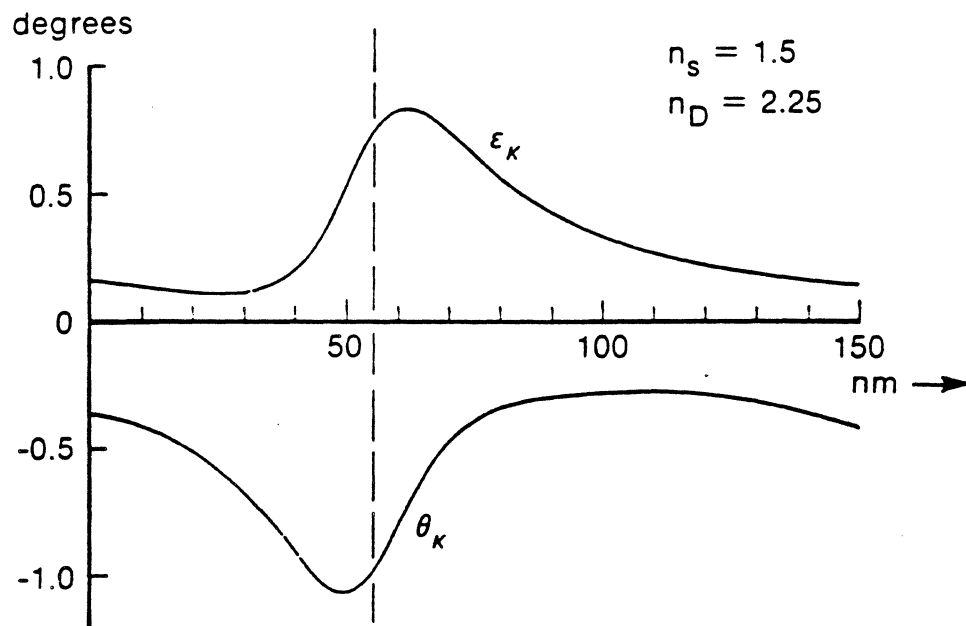
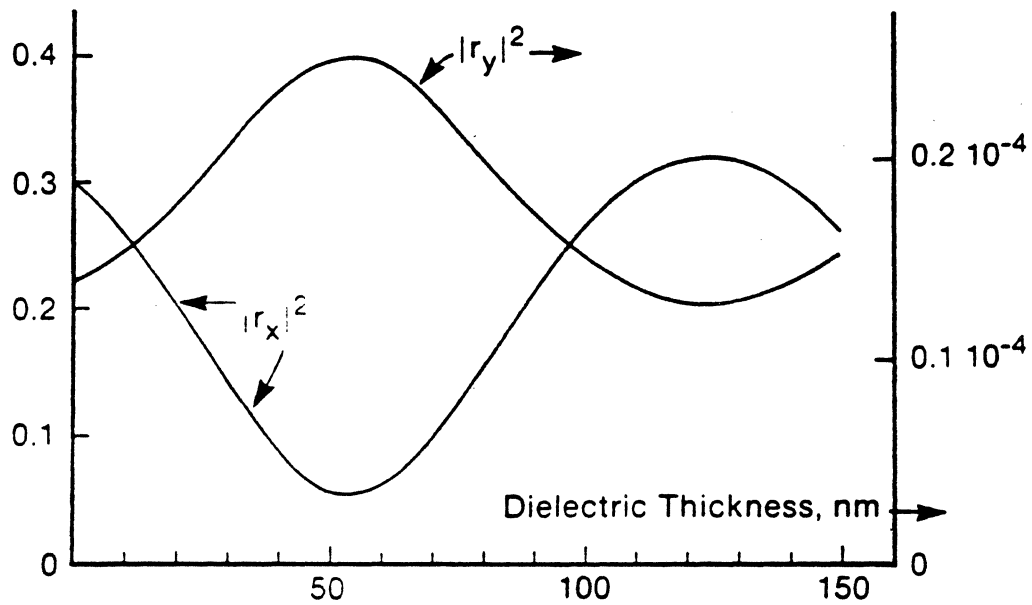
$$\tilde{r}_x = 1/2(\tilde{r}_+ + \tilde{r}_-) = r_x e^{i\delta_y}$$

$$\tilde{r}_y = 1/2i(\tilde{r}_+ - \tilde{r}_-) = r_y e^{i\delta_y}$$

$$\theta_k = -1/2(\delta_+ - \delta_-)$$

$$E_k = - \frac{r_+ - r_-}{r_+ + r_-}$$

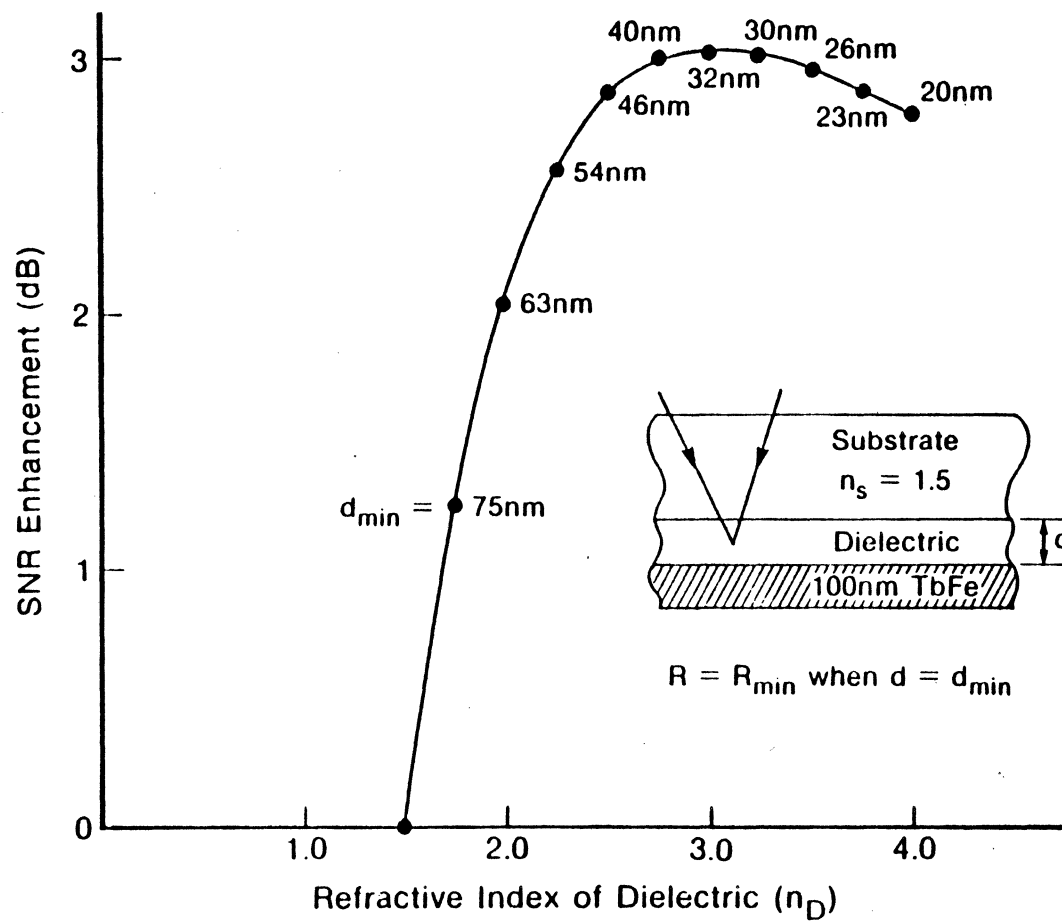
Dielectric Enhanced Single Layer



Handwritten notes:
 $\lambda = 633 \text{ nm}$
 $n_s = 1.5$
 $n_D = 2.25$
 $d = 50 \text{ nm}$

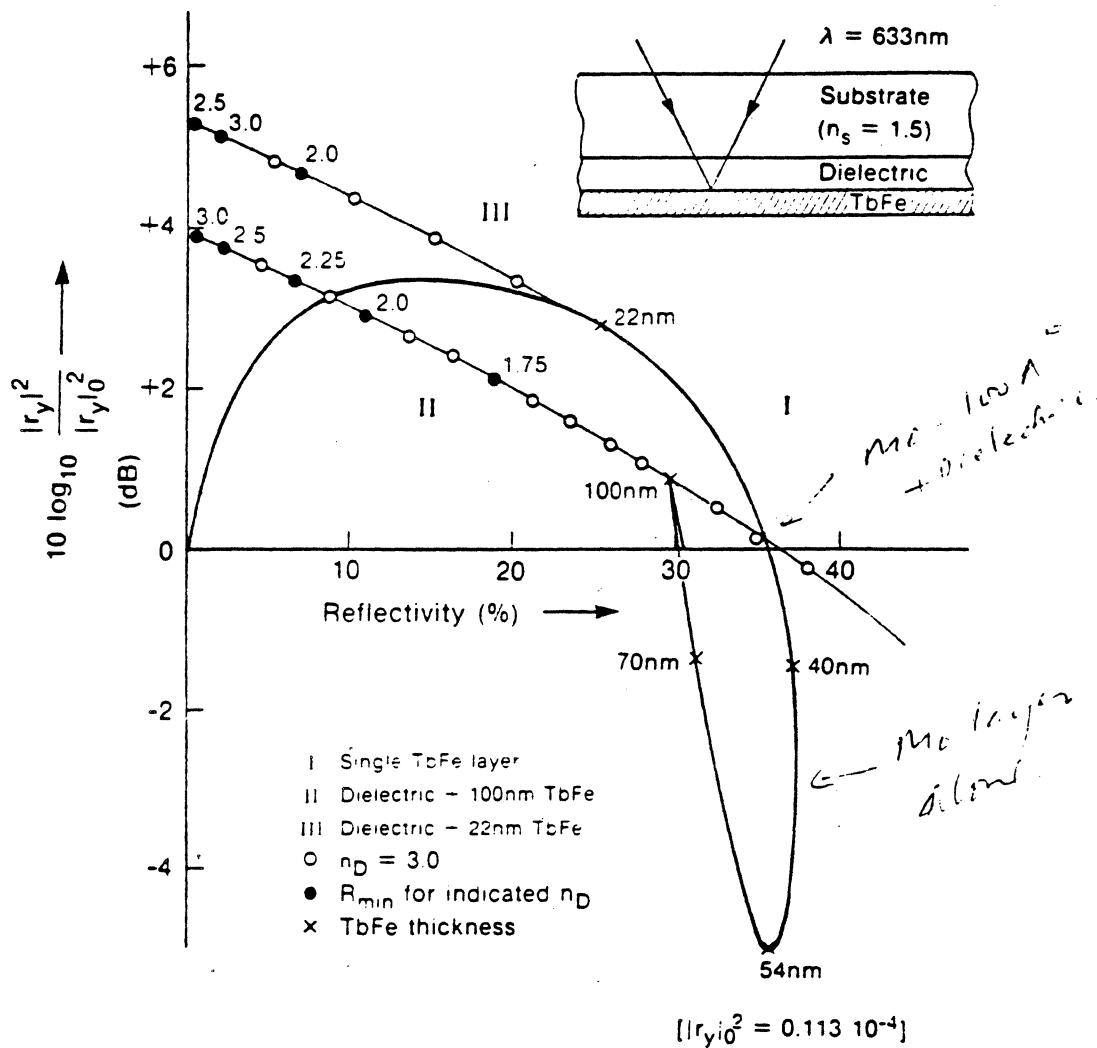
Single Layer — Dielectric Enhancement

maximum



220 Å Mo + Dielectric

Single Layer



MAGNETO-OPTIC STATUS

<u>Company</u>	<u>Media</u>	<u>Density</u> Mbi ²	<u>Data Rate</u> MB/s	<u>CNR</u> dB	<u>R/W Powe</u> mW inc.
CANON	GdTbFeCo	-	-	45	7/2
DAICEL	GdTbFe	-	-	50	5/1
MEI	GdTbFeGe (P)(PM)	250	0.3	49	9/1-8
NHK	GdTbCo (P)(G)	-	0.75	40-43	10/1
NIKON	TbFe/GdFeCo (G)	-	1.25/0.3	48/55	8.7/3.7
OLYMPUS/KDD	GdTbFe (P)(PM)	250	0.3	48	7/1.1
PHILIPS	GdTbFe	258	0.125	44	8/1
RICOH	TbFeCo	-	-	45	-
SHARP	GdTbDyFe (P)(G)	140	0.50	50	5/1
SONY/KDD	TbFeCo (P)(PM)	320	0.25	52	7/1
3M	RE-TM	300	2.0	>50	12/3
XEROX	RE-TM (A)	-	1.25	56	8/1

minchi

P - Pregroove: Pm-PMMA: G-Glass: A-Aluminum Substrates

MAGNETO-OPTIC DATA STORAGE

- Rare Earth/Transition metal alloy media are the leading candidates
- Multilayer interference coatings are important to achieving adequate SNR
- Cyclability is good, $> 10^7$ cycles reported
- Data retention is good
- The drive technology is in place now
- Overwrite requires sequential erasure followed by re-write
- The chemical and magnetic stability of thin RE-TM films is not yet established

Systems and Applications—Future Trends

Al Hoagland, SCU
Institute for Information
Storage Technology

CONTENTS

MEMORY & STORAGE HIERARCHIES

RECORDING/DASD

SCALING (GEOMETRICAL PARAMETERS)

COMPONENT TRENDS

SERVO & DRIVE DESIGN ISSUES

SUB-SYSTEM PERFORMANCE

OTHER STORAGE HARDWARE APPROACHES

FUTURE DIRECTIONS

MAGNETIC

OPTICAL

MAGNETIC VS. OPTICAL

REFERENCES

EVOLUTION OF TECHNOLOGY

PERIPHERAL STORAGE

MAGNETIC TAPE

1940s

MAGNETIC DISK

1956

1984

MAIN MEMORY

RELAY

VACUUM TUBE

MERCURY DELAY LINE

CRT STORAGE TUBE

MAGNETIC CORE

TRANSISTOR

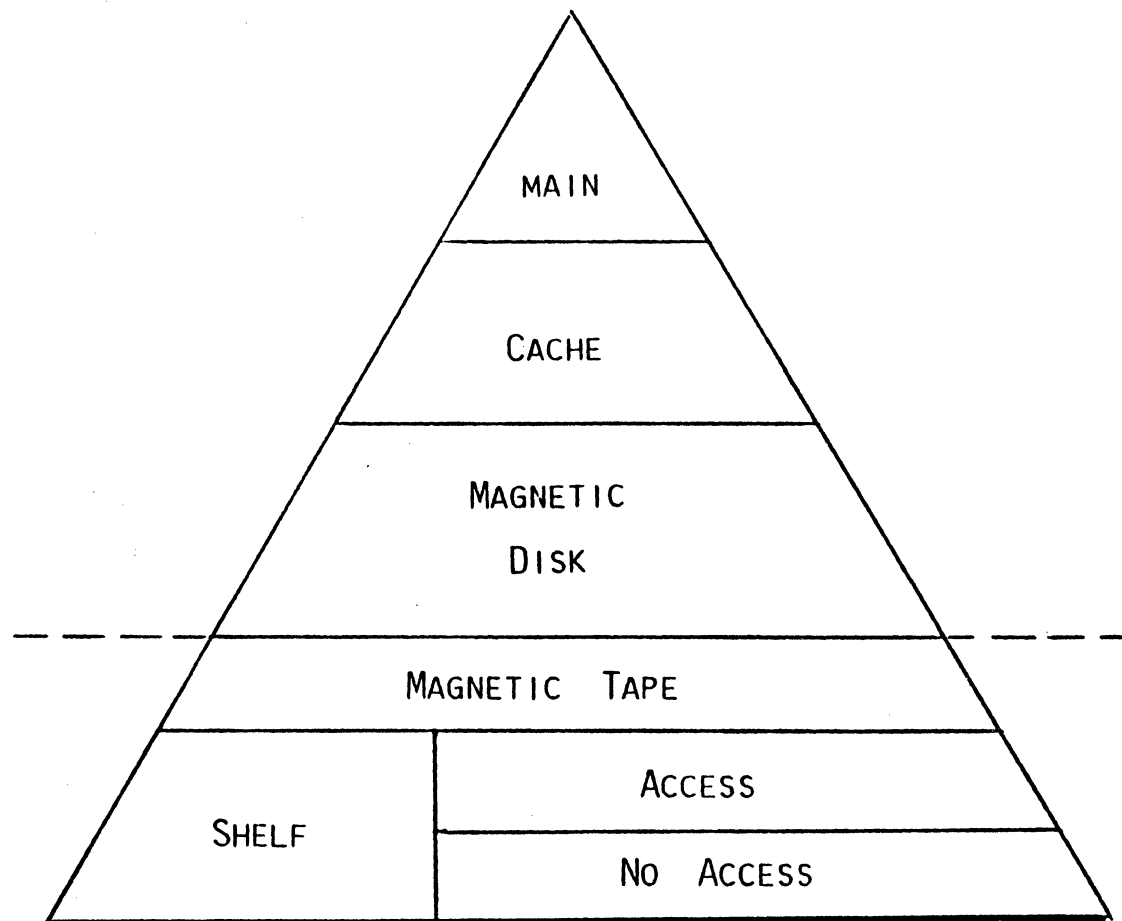
LSI SILICON

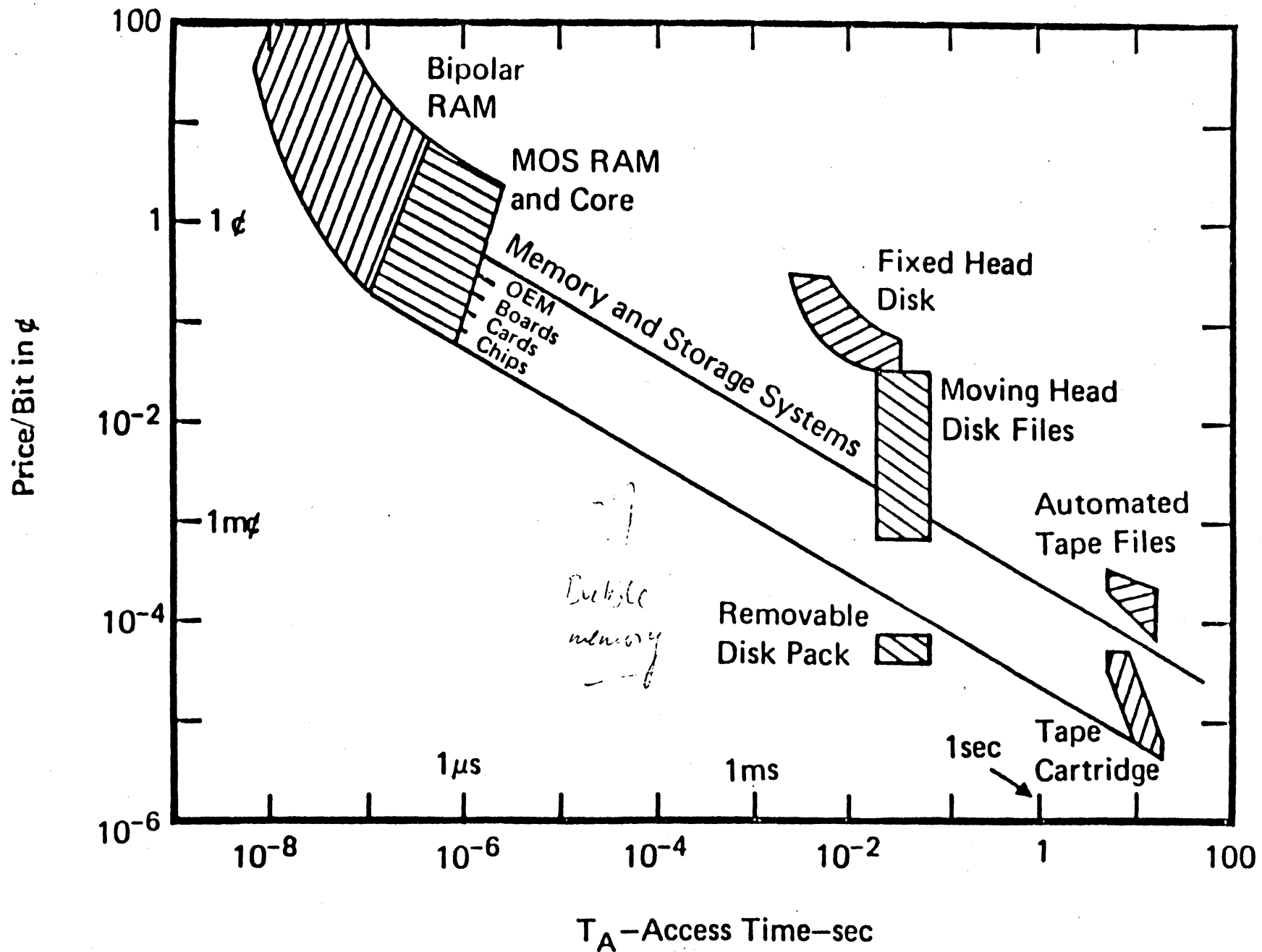
VLSI SILICON

GALLIUM ARSENIDE

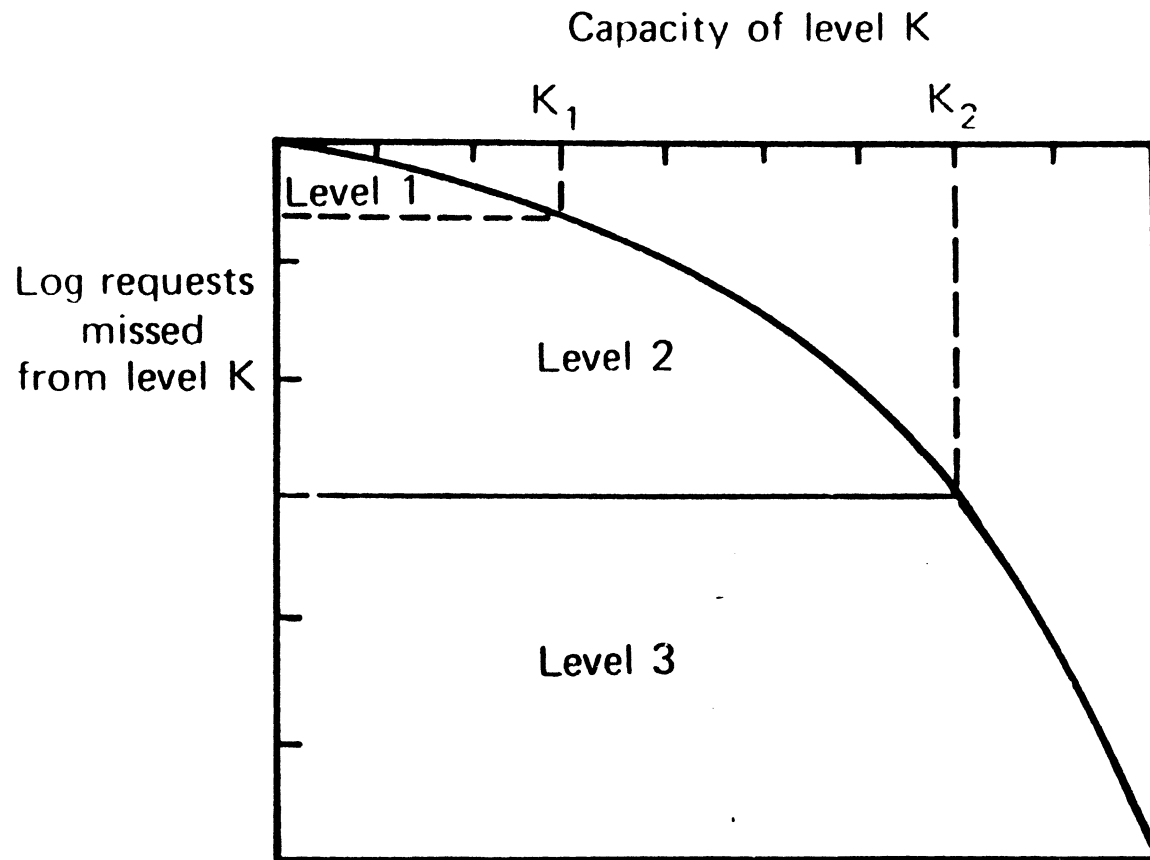
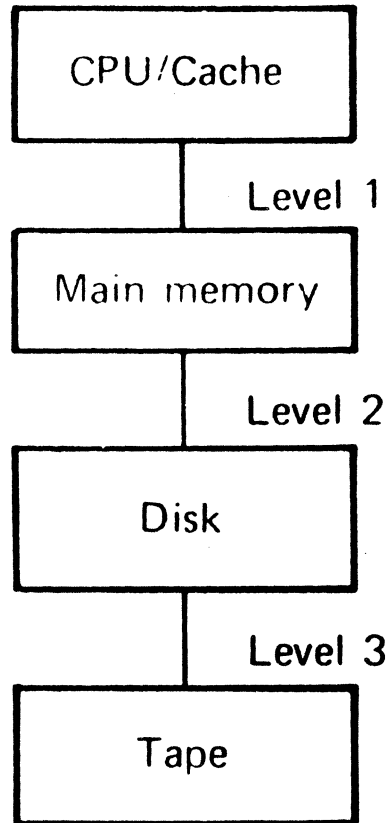
?

STORAGE HIERARCHY

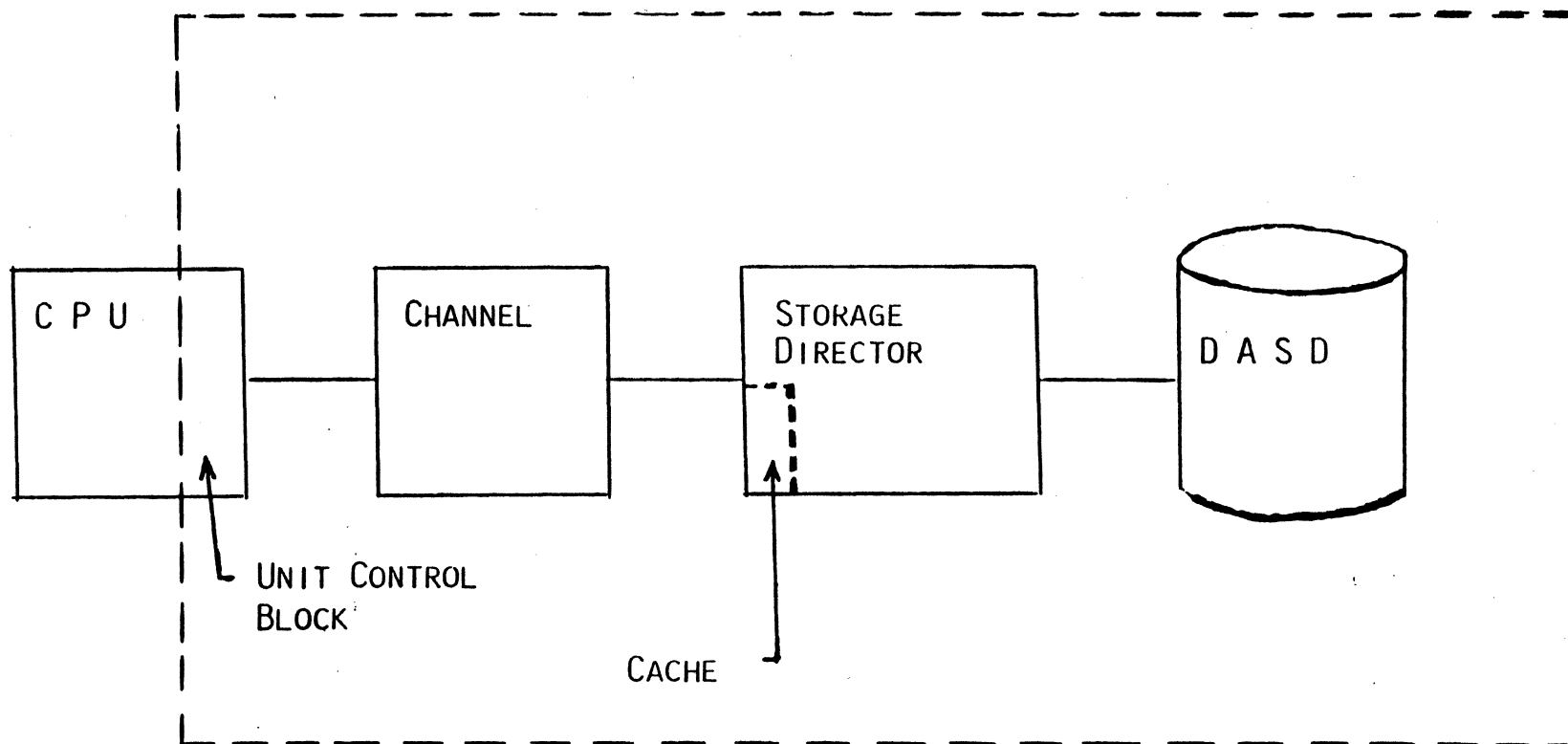




3 - Level Hierarchy



STORAGE SUBSYSTEM



Recording Technologies

- Magnetic Recording
Invention—1898
DASD—1956 (100 bpi, 20 tpi)
- Optical Recording
Photostore (single disk)—1952
(approx. 2000 bpi, 2000 tpi)

How do you measure progress?

high only

Areal Density as Goal

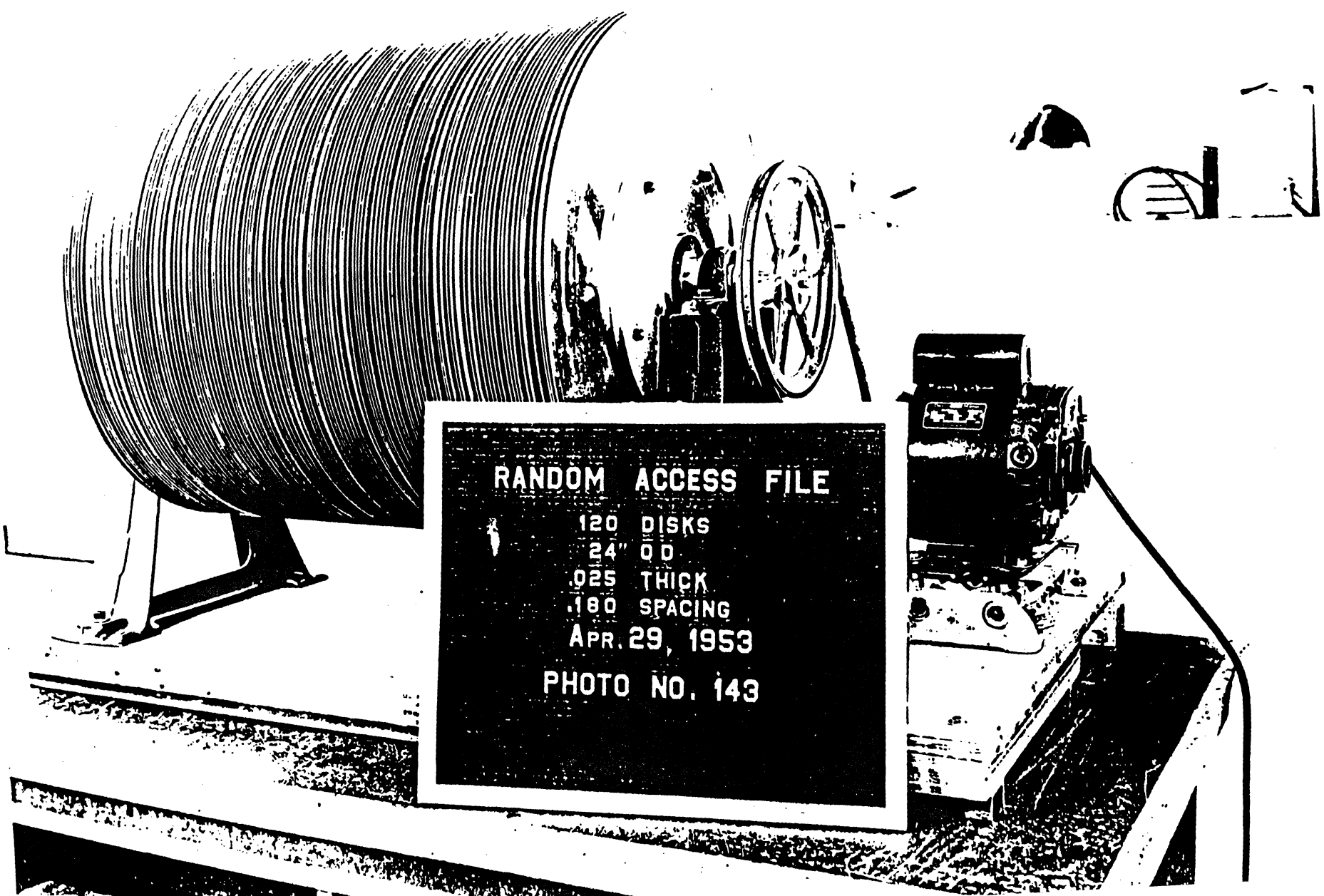
- **Advantages**
 - **For Specific Hardware Configuration**
 - Greater Capacity**
 - Lower Cost/Bit**
 - **For Same Capacity**
 - Smaller Module**
 - Improved Access Capabilities**
 - Reduced Cost**
- Whereas
- **Access Time**
 - **Configuration Choice Dominant Factor**

Areal Density as Goal (cont.)

- **Data Rate**
 - **Most Sensitive to Degree of Read/Write Parallelism**

Magnetic Recording as Standard for Judging Alternatives

- **Advantages**
 - **Updating Capability**
Investment in Software
 - **Nonvolatile**
 - **Large Capacity at Lowest Cost per Bit**
- **Disadvantages**
 - **Relatively Long Access Time**
 - **Mechanical Reliability Issues**



RANDOM ACCESS FILE

120 DISKS

24" OD

.025 THICK

.180 SPACING

APR. 29, 1953

PHOTO NO. 143

RIGID DISK TRENDS

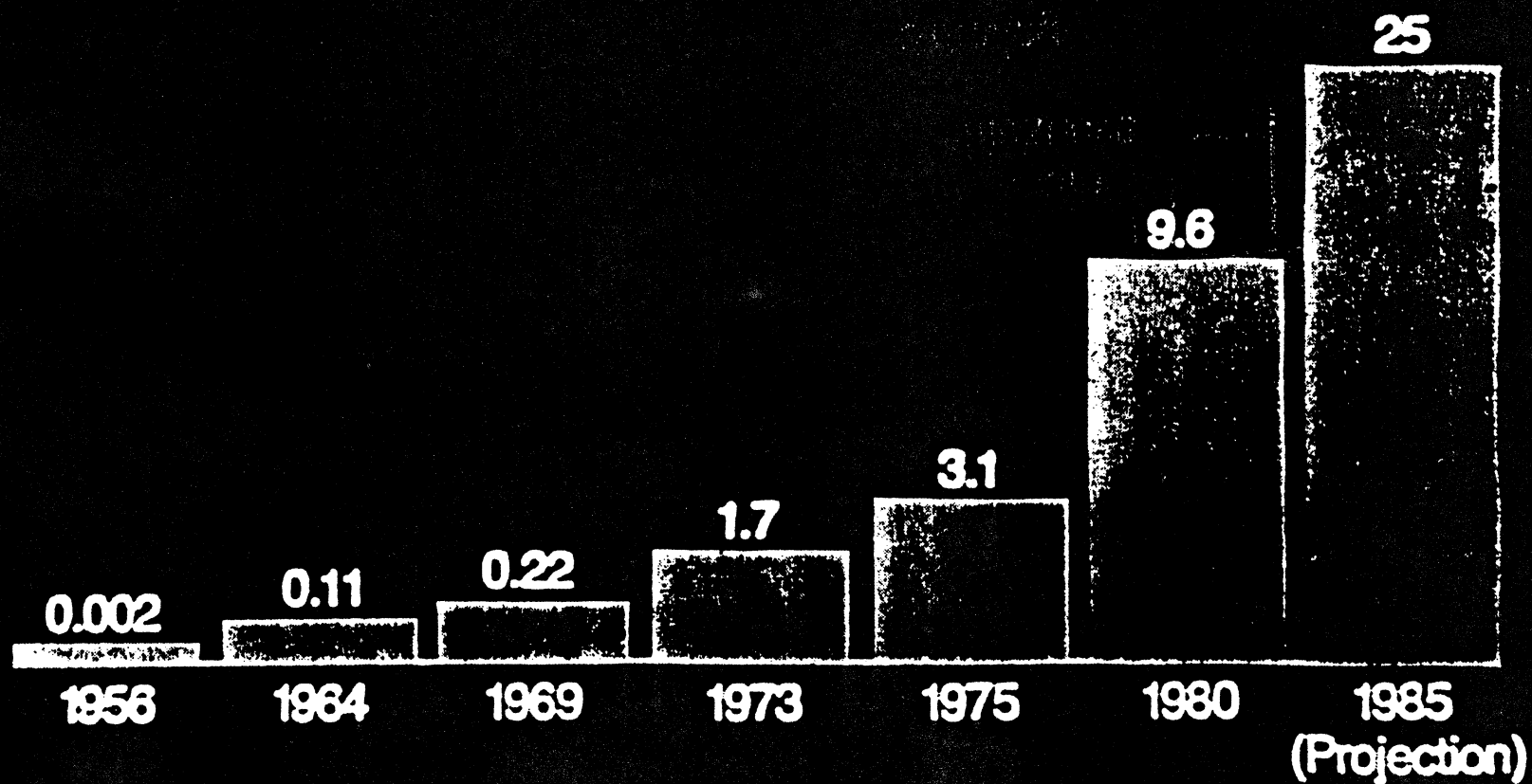
YEAR	DEVICE	BITS/IN	TRACKS/IN	BITS/IN ²	IN MICRO INCHES		
					SPACING	GAP	THICKNESS
1956	IBM 350	100	20	2000	1000	800	1200
1961	IBM 1301	500	50	25000	500	500	500
1964	IBM 2311	1100	100	110000	125	200	250
1965	IBM 2314	2200	100	220000	85	105	85
1970	IBM 3330	4040	192	775680	50	100	41
1973	IBM 3340	5600	300	1.68 x 10 ⁶	17	60	41
1975	IBM 3350	6425	476	3.06 x 10 ⁶	17	60	41
1978	STC 8650	6425	952	6.12 x 10 ⁶	17	60	40
1979	IBM 3370	12134	635	7.71 x 10 ⁶	15	24	35
1980	IBM 3380	15000	801	1.20 x 10 ⁷	11	24	26
1981	NTT PATTY	13970	1092	1.53 x 10 ⁷	8	32	7
1984	NTT PATTY	25400	1800	4.57 x 10 ⁷	6	20	7
1985	IBM 3380(E)	15000+	~1400	~20.0+ x 10 ⁷ *			

*ELECTRONIC NEWS

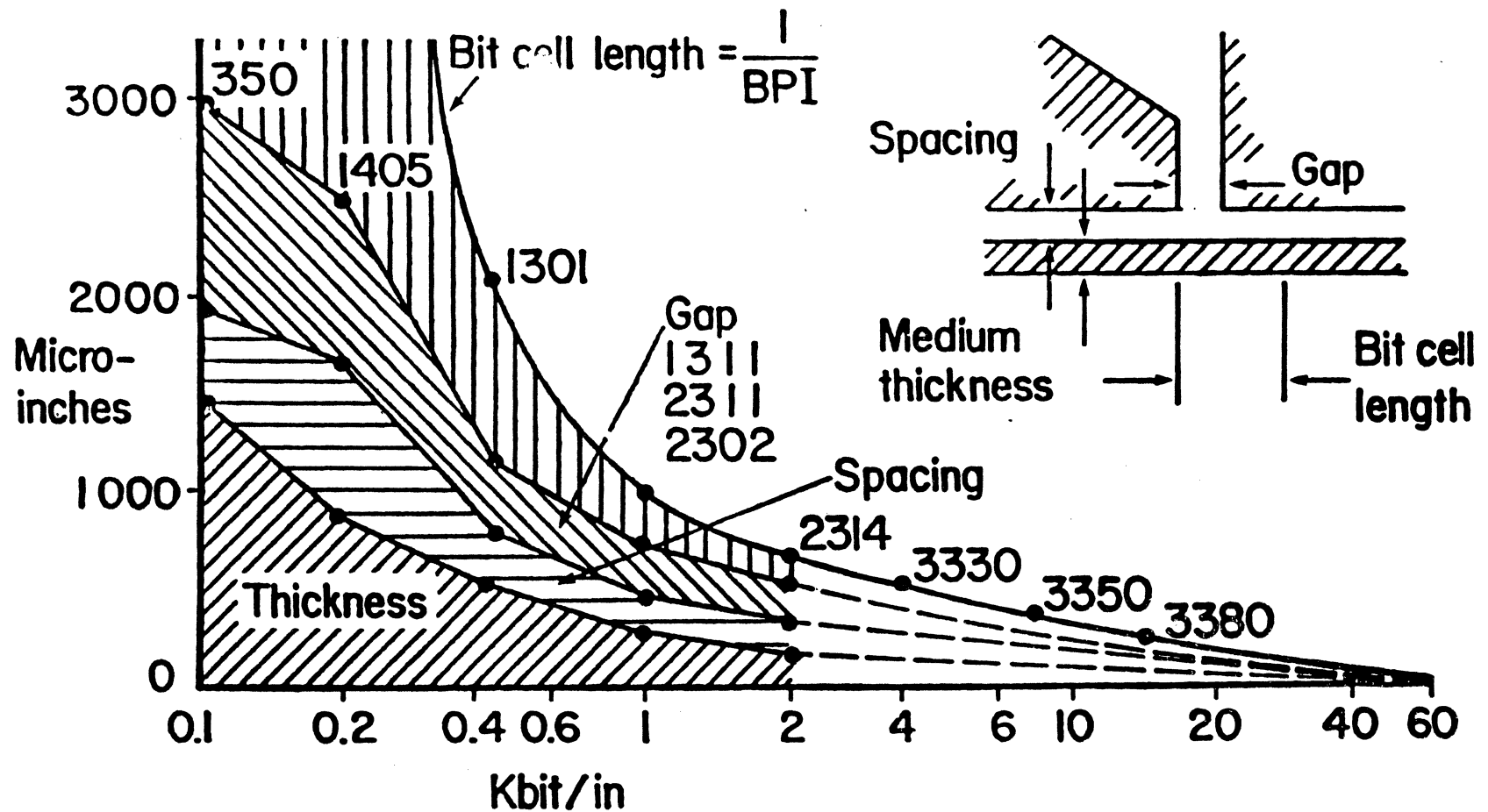
TREND LARGE DISK

	<u>COST</u> <u>\$/MB/Mo.</u>	<u>ACCESS</u> <u>TIME</u> <u>MS</u>	<u>CAPACITY</u> <u>MB/SPINDLE</u>
1956			
350(RAMAC)	130	600	5
1965			
2314	22.49	75	29
1970			
3330-1	7.98	30	100
1975			
3350	2.86	25	317
1980			
3380	.94	16	1,260
3380(E)			2,520

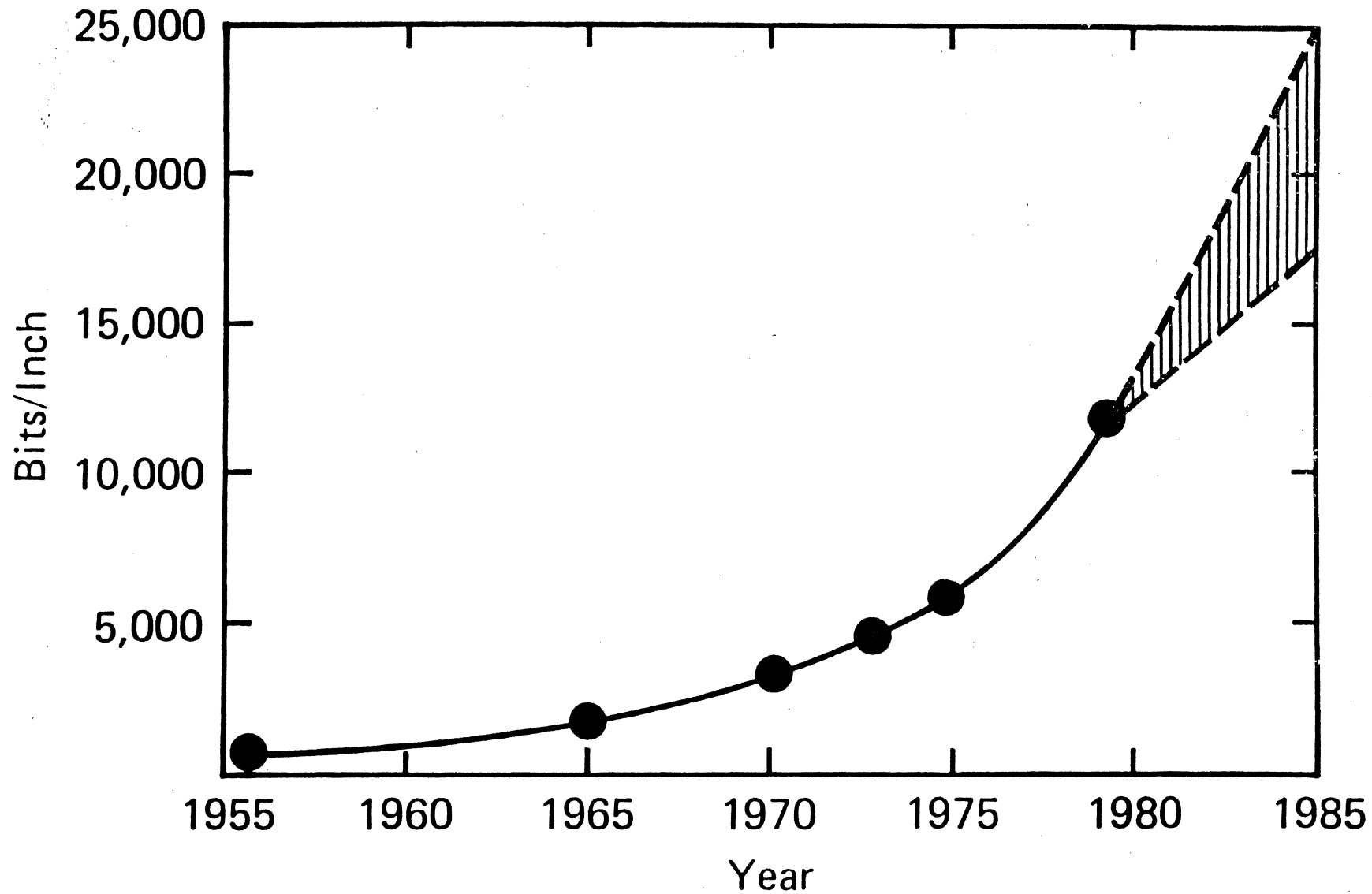
Megabits per Square Inch

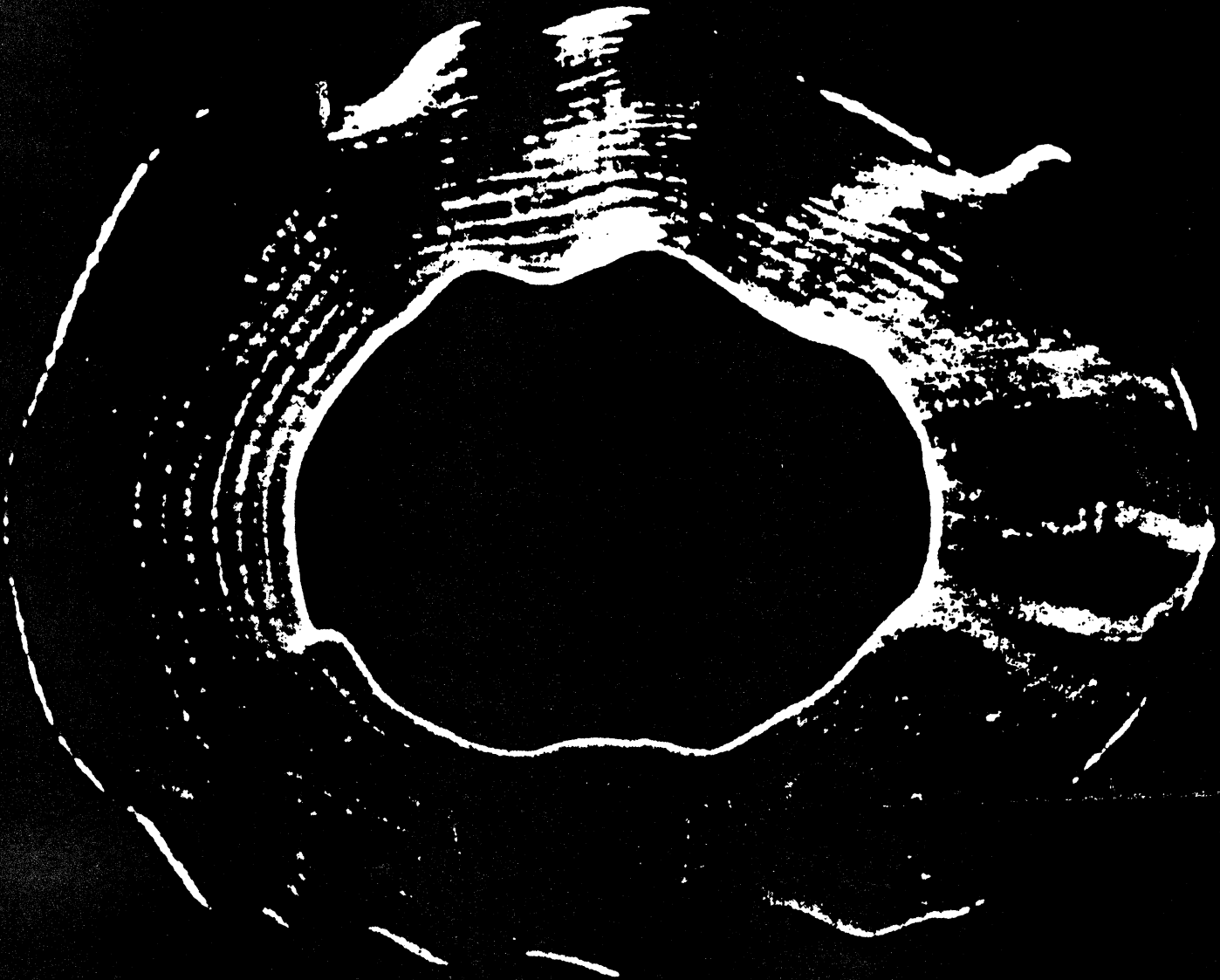


Bit cell length is related to physical recording parameters

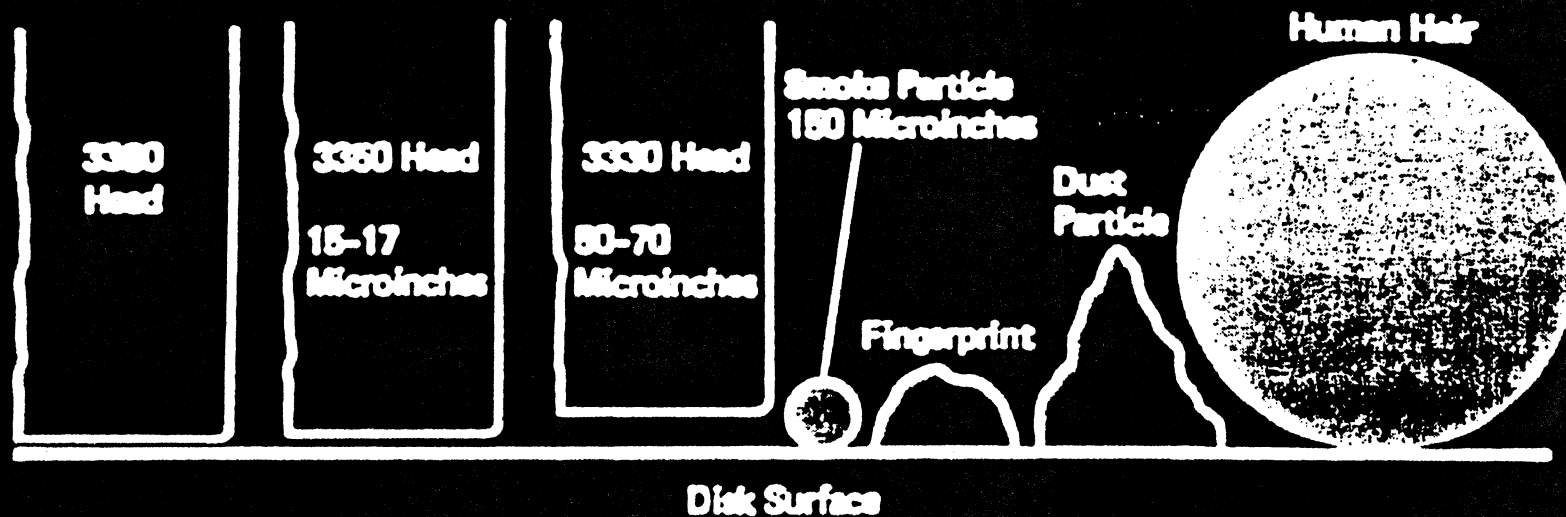


Disk Storage Trends — Bit Density



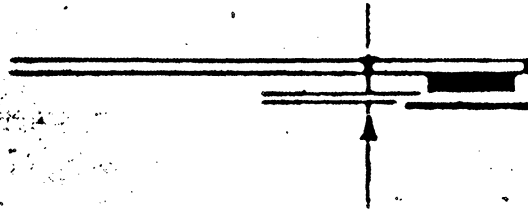


Head Flying Height



Flight Height Analogy

20 millionths of an inch



1 Revolution

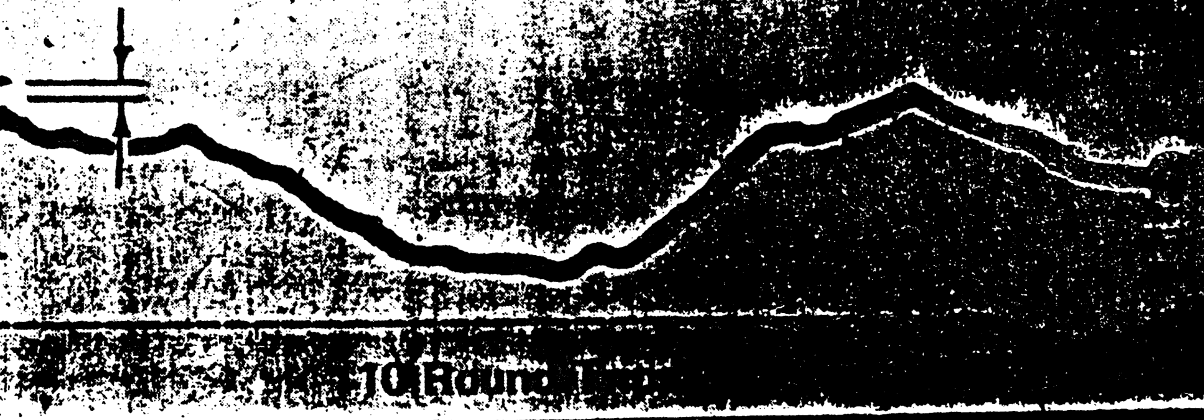
.....is roughly equivalent to:

10,000 ft.



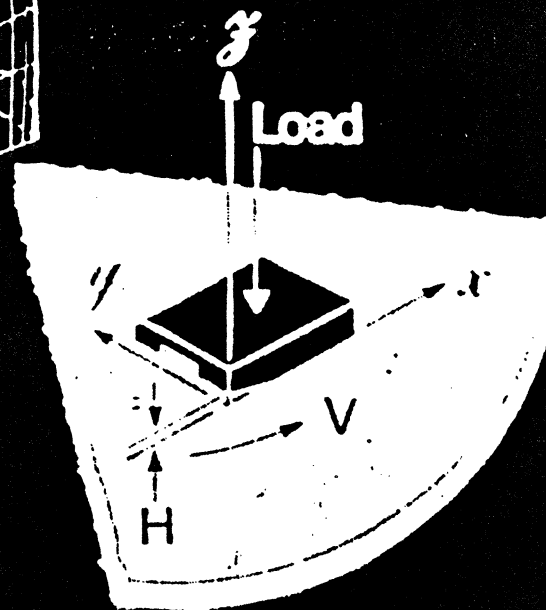
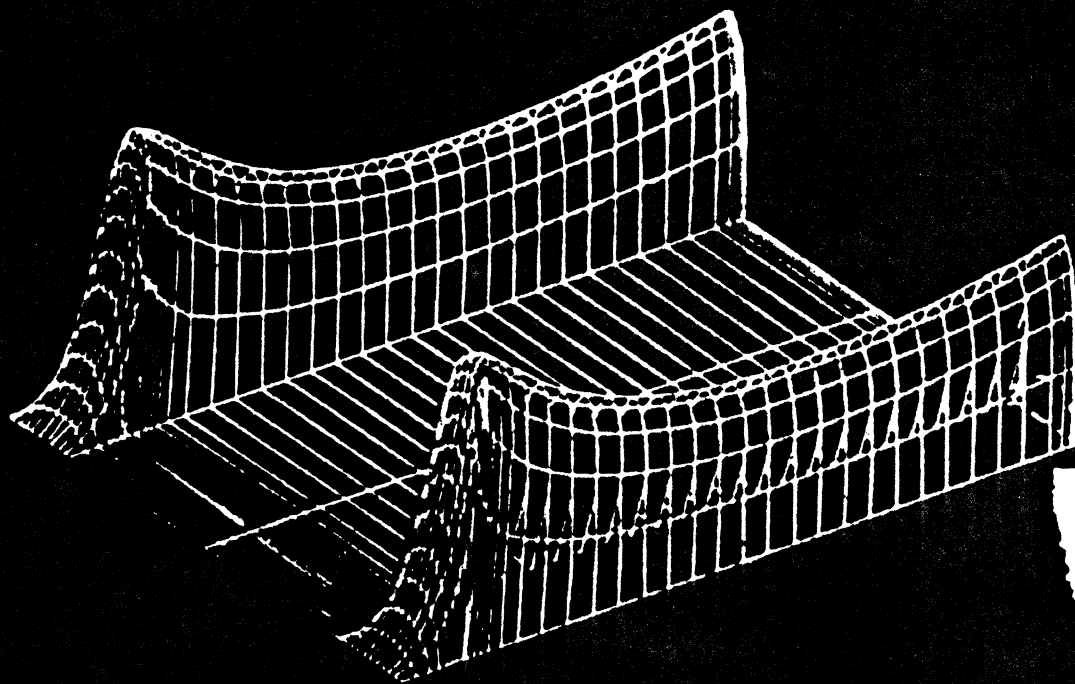
San Francisco

100 ft.



10,000 ft.

$$\nabla \cdot [H^3 P \nabla P + 6\lambda_a P_a H^2 \nabla P - 6\mu V P H] = 12\mu \frac{\partial(PH)}{\partial t}$$



How Small is Small?

100 Å = Biological Molecule

200 - 500 Å = Magnetic Thickness Metal Film Disk

2000 Å = Minimum Base Width for Transistors

0.25 μ = Head-Disk Spacing

0.45 μ = Wave Length of Blue Light

0.6 μ = Head Gap (Disk)

10,000 Å = 1 μ = 1 Micron = 10⁻⁶ Meters

How Small is Small? (Continued)

0.65μ = Wave Length of Red Light

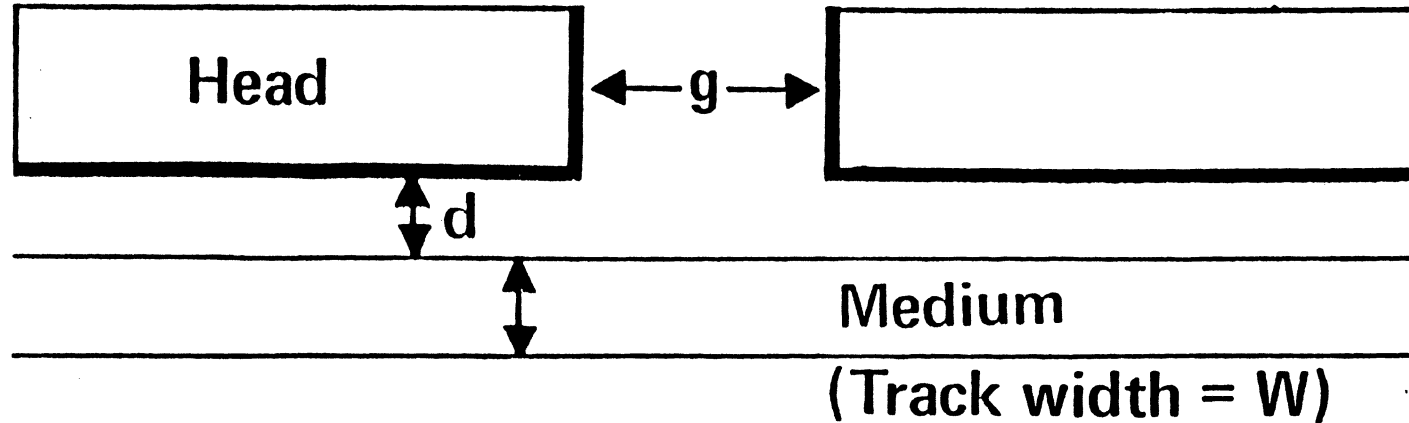
1.5μ = Groove Width in Video Disk

25μ = Track Width - Disk

50μ = Thickness of Human Hair

100μ = Thickness of Typical Paper Sheet

Readback Loss Factors



loss factors $e^{\alpha N \frac{d\phi}{dt}} \propto NW \times [\text{loss factors}]$

spacing $e^{\frac{-2\pi d}{\lambda}} \sim e^{-\pi d(fci)}$

gap (or pole) $\frac{\sin \frac{\pi g}{\lambda}}{\frac{\pi g}{\lambda}} \sim \frac{\sin \frac{\pi g(fci)}{2}}{\frac{\pi g(fci)}{2}}$

thickness $1 - e^{\frac{-2\pi \delta}{\lambda}} \sim 1 - e^{-\pi \delta(fci)}$

Geometrical Loss Factors on Readback

$$\text{Spacing Loss} = 27.3 \times d \times \text{fci} \text{ (db)}$$

$$\text{Gap Loss} = \sin \frac{[\pi/2 (g \times \text{fci})]}{\pi/2 (g \times \text{fci})}$$

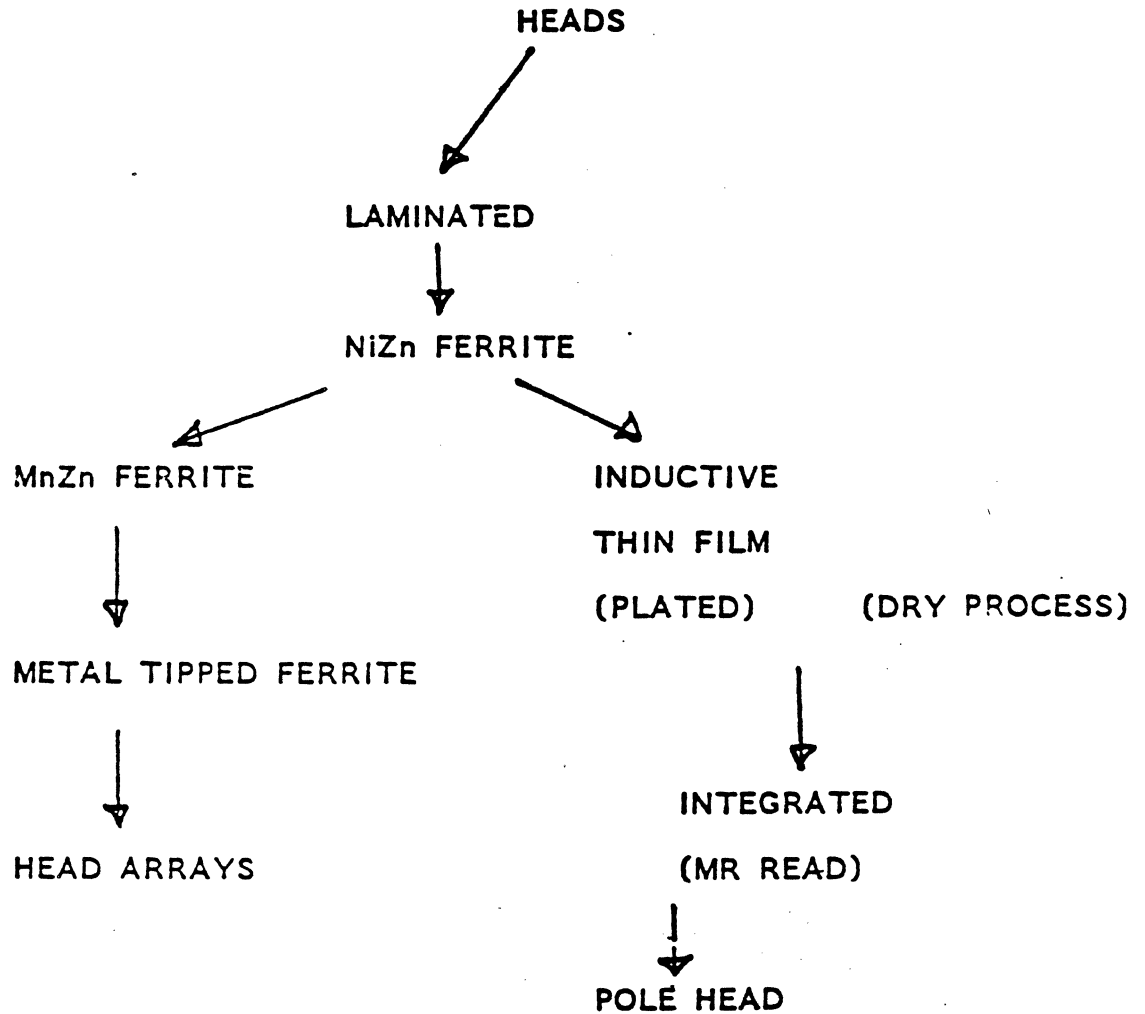
Example:

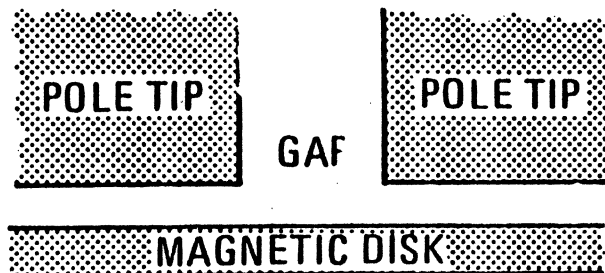
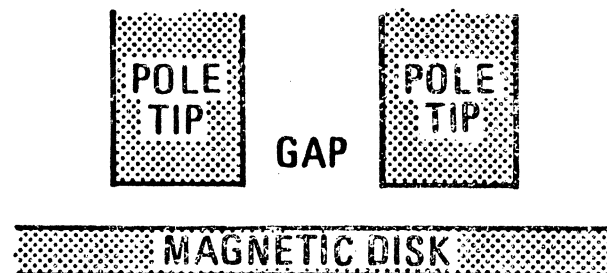
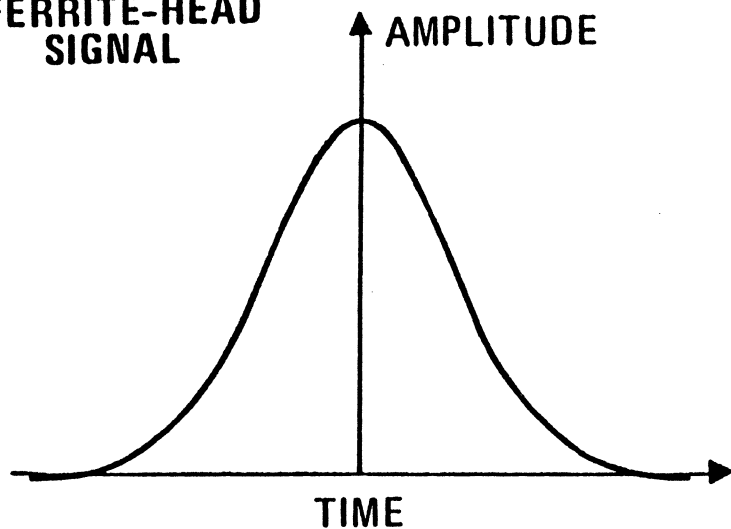
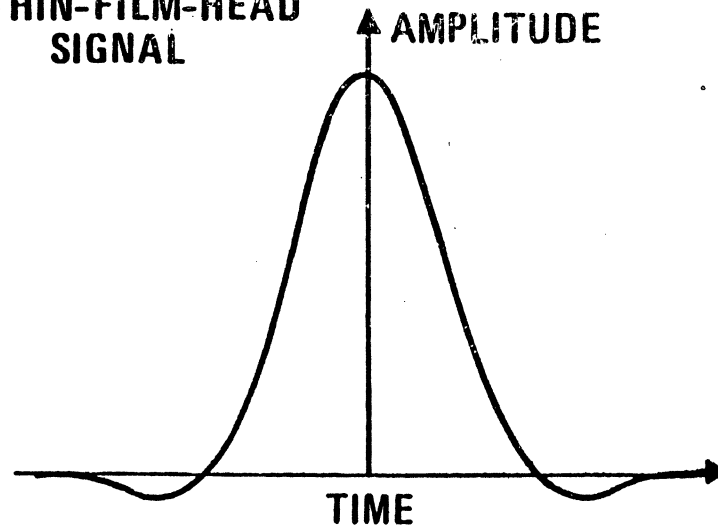
$$\text{fci} = 50,000$$

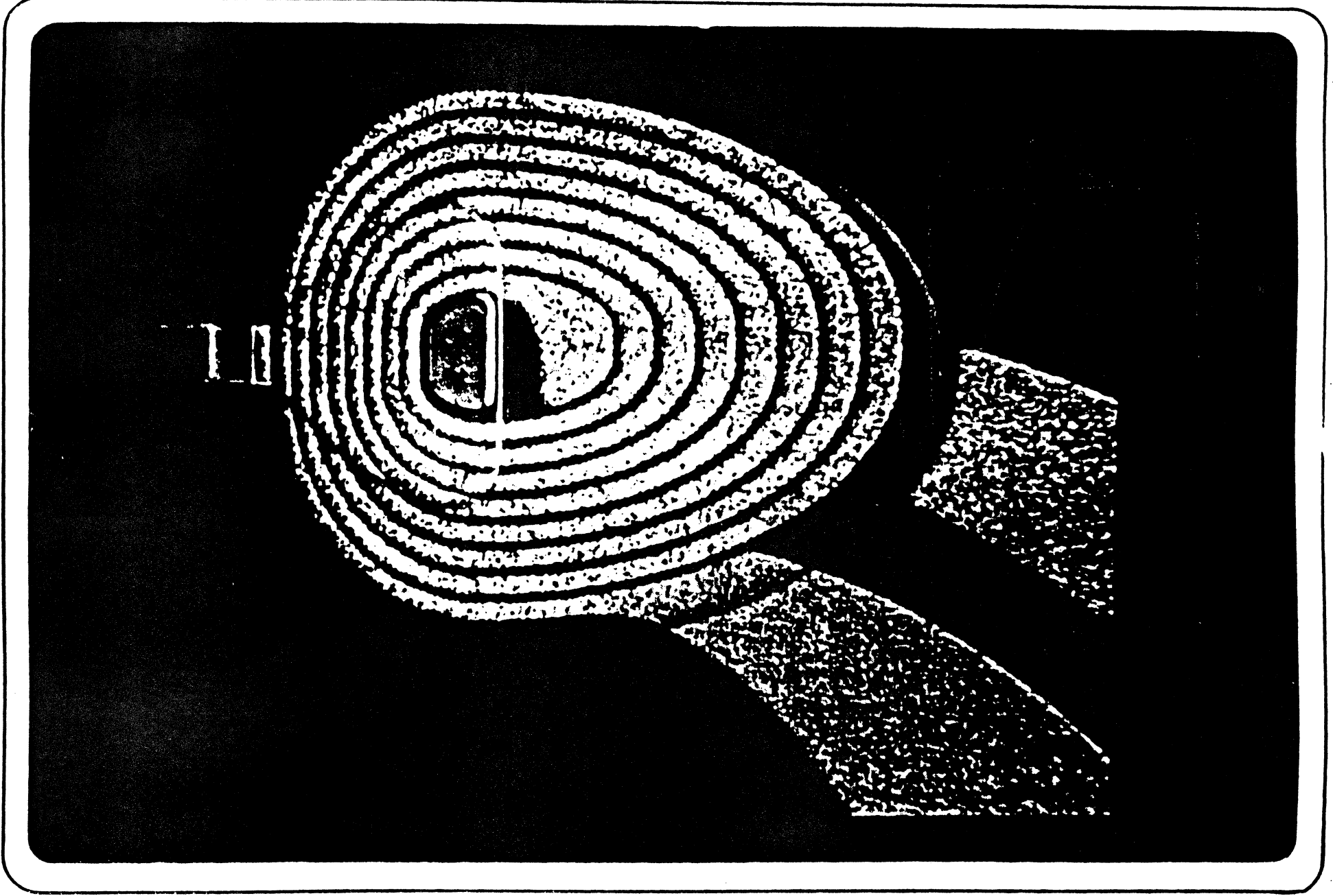
3db loss due to spacing occurs at $d = 2\mu$ in.

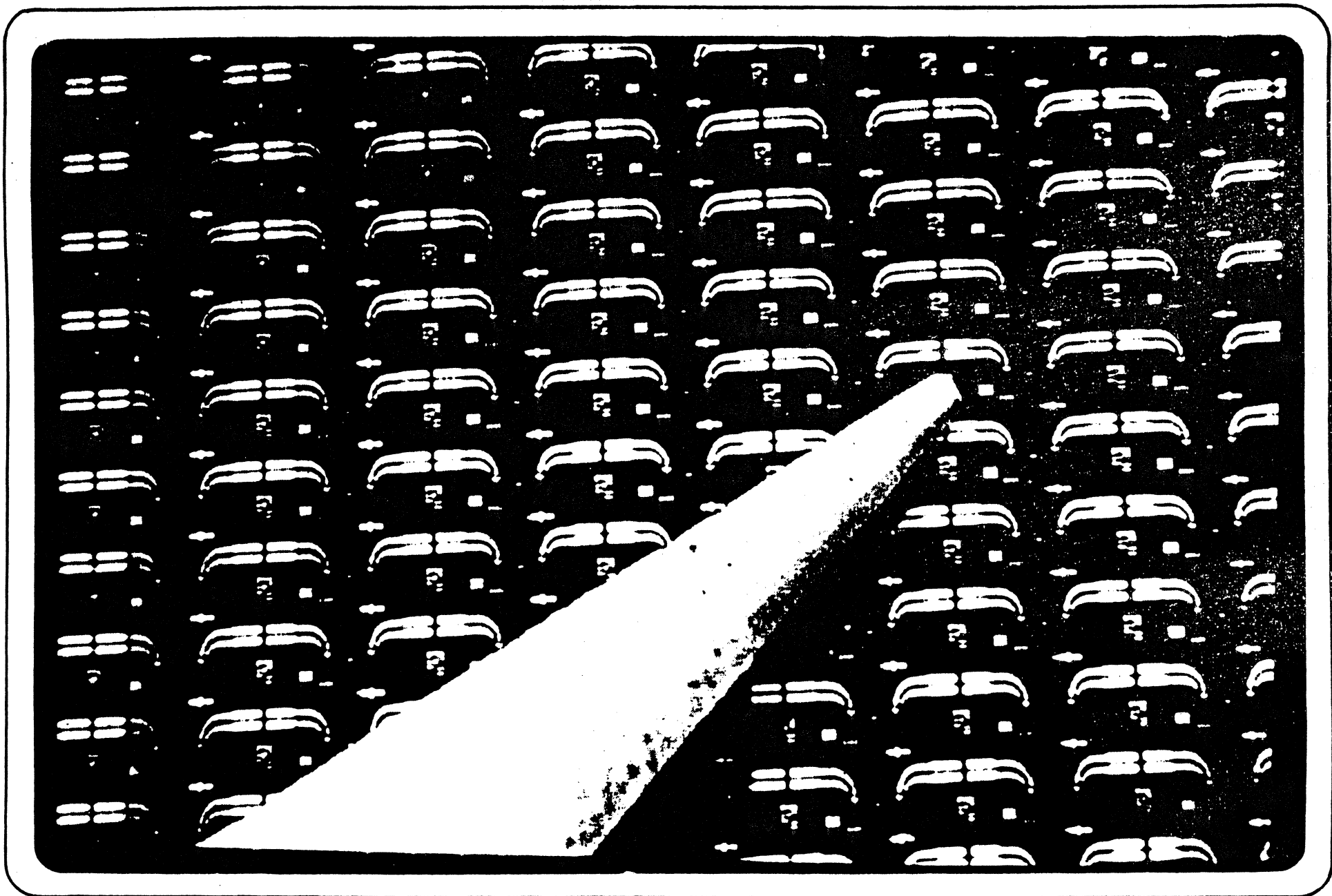
3db loss due to gap occurs at $g \approx 20\mu$ in.

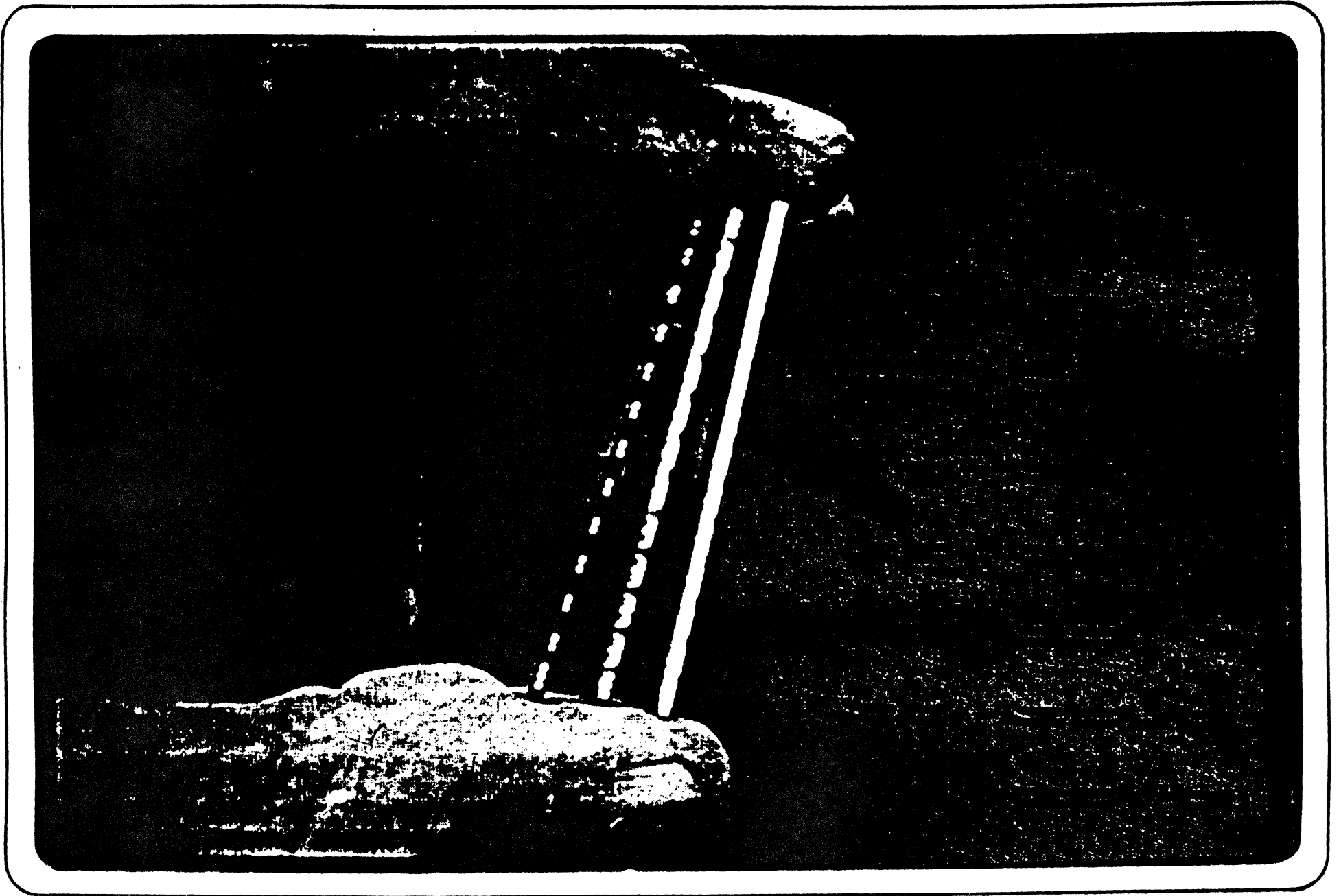
TECHNOLOGY TRENDS

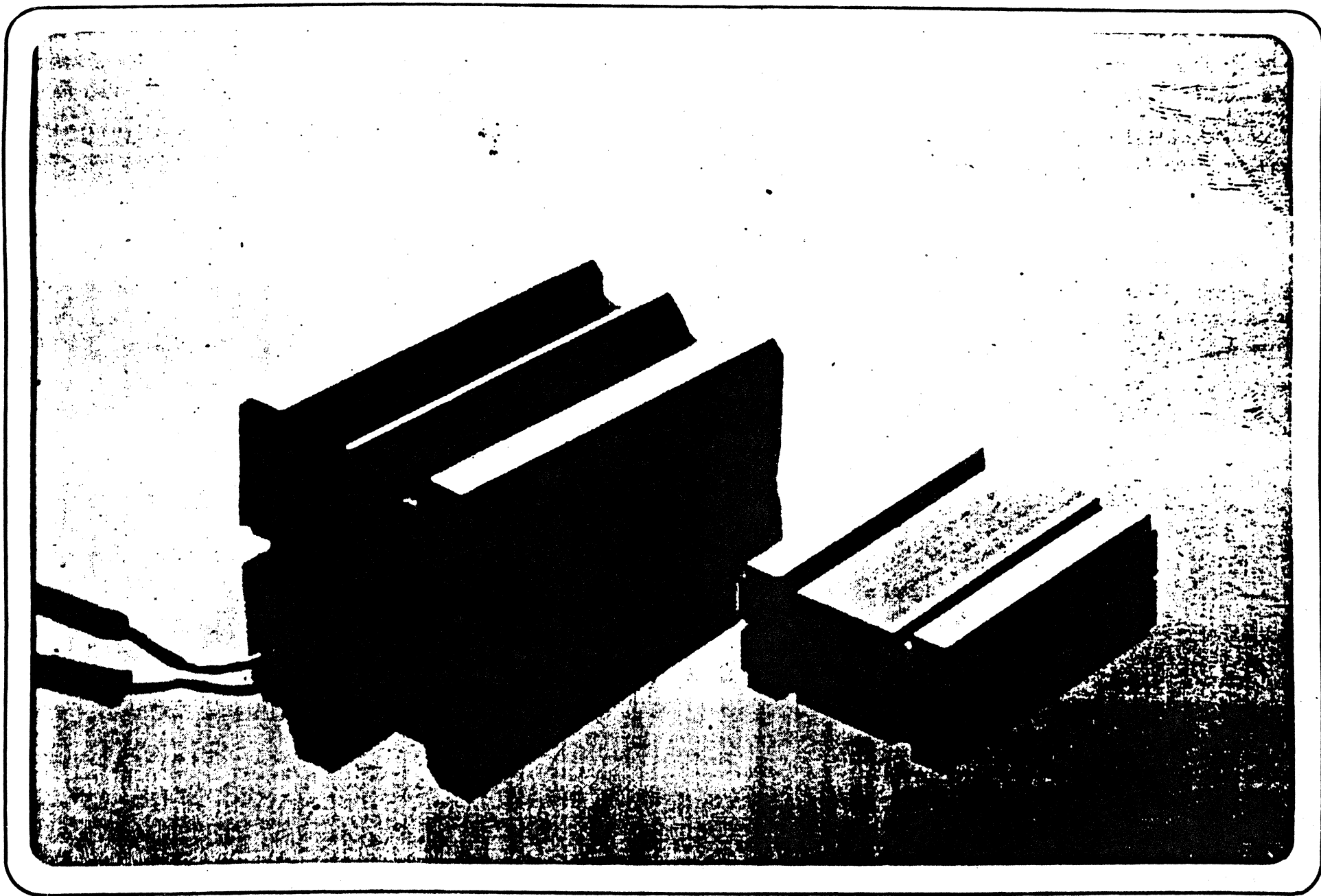


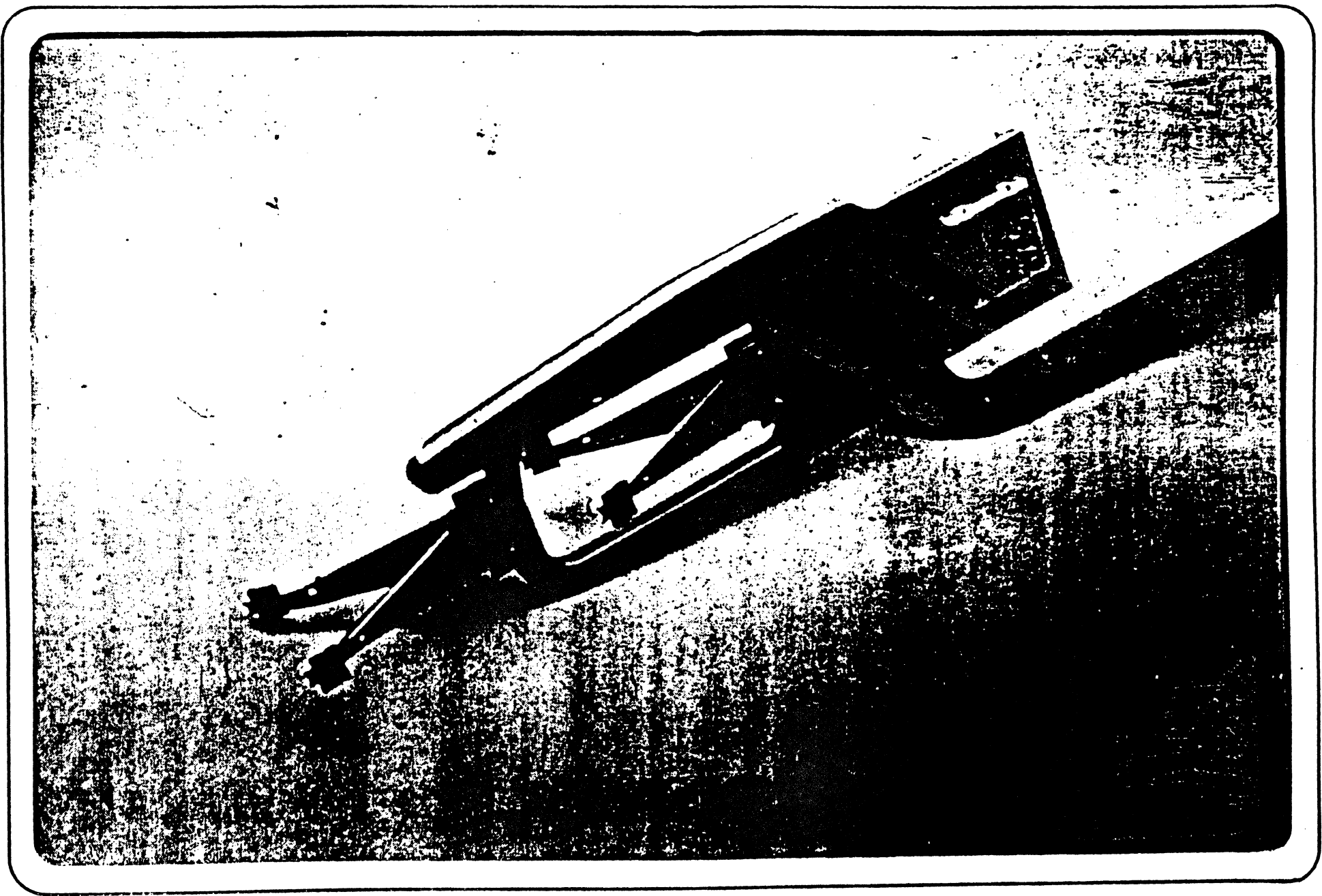
FERRITE HEAD**THIN-FILM HEAD****FERRITE-HEAD
SIGNAL****THIN-FILM-HEAD
SIGNAL**





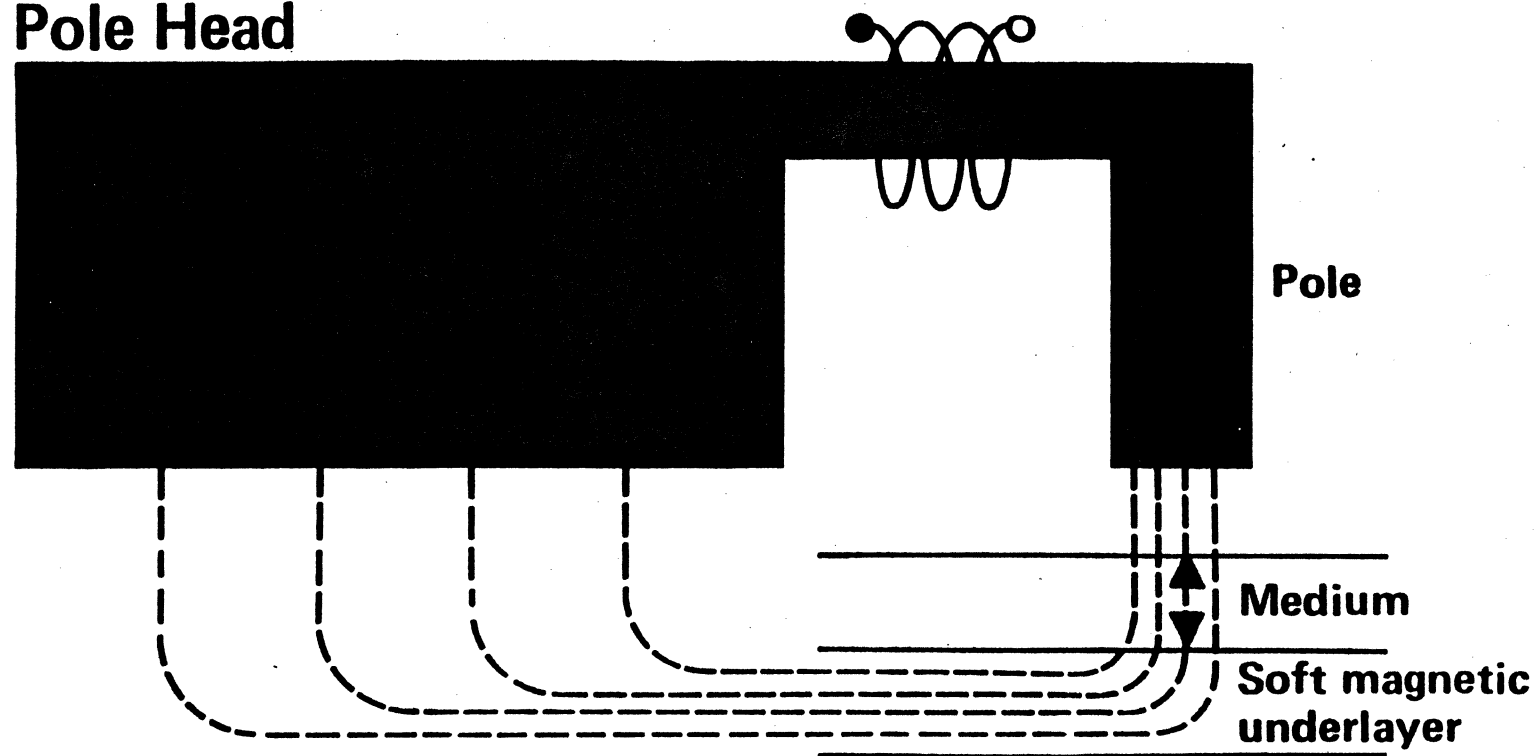






Vertical

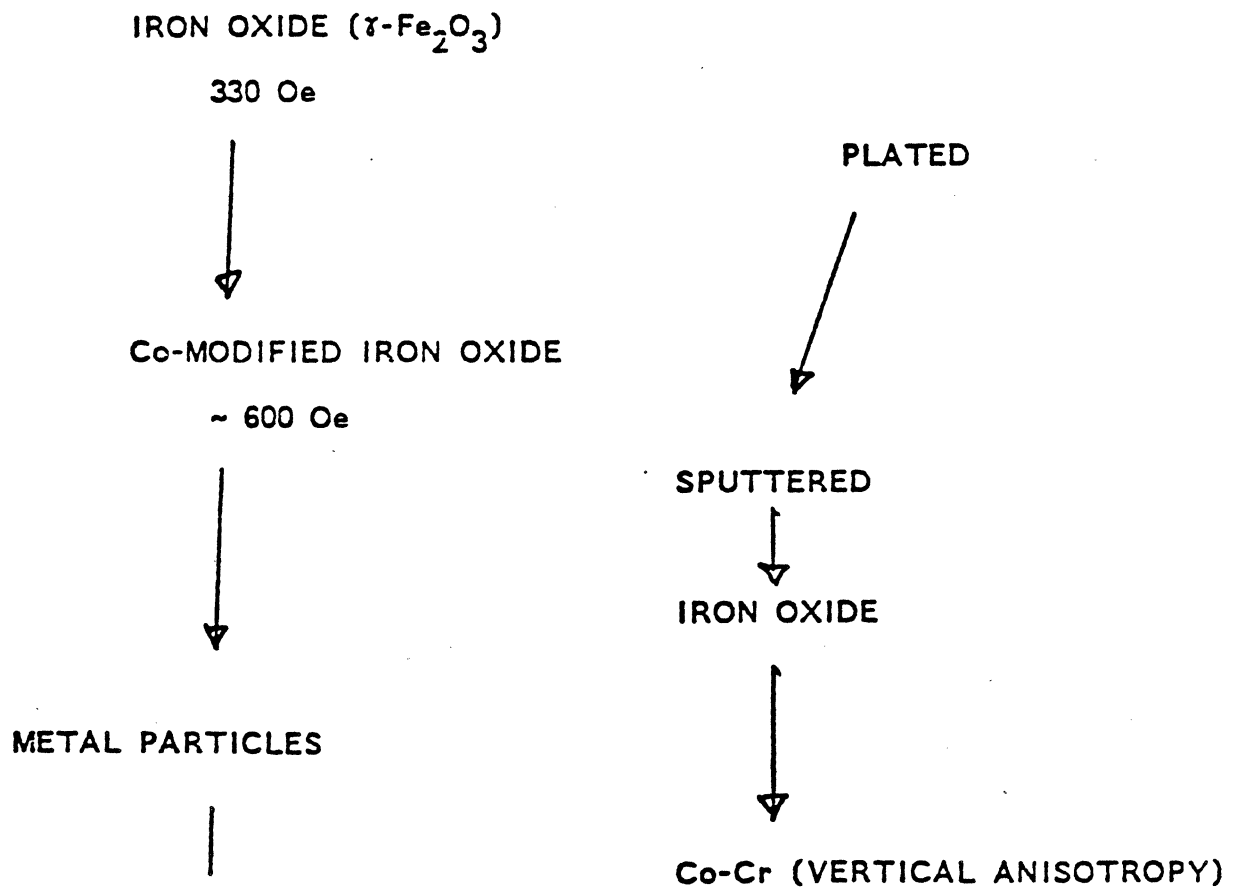
Pole Head



TECHNOLOGY TRENDS

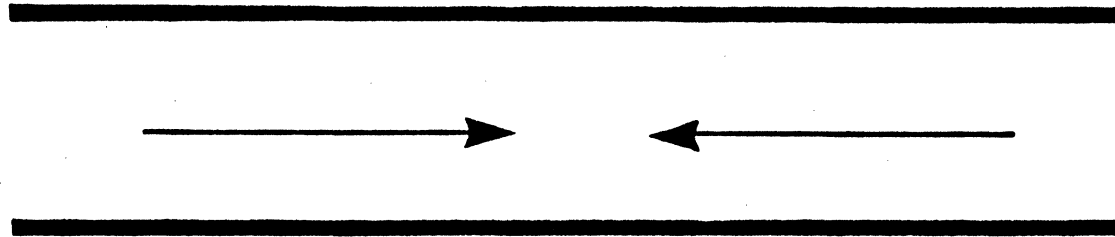
MEDIA

- PARTICULATE

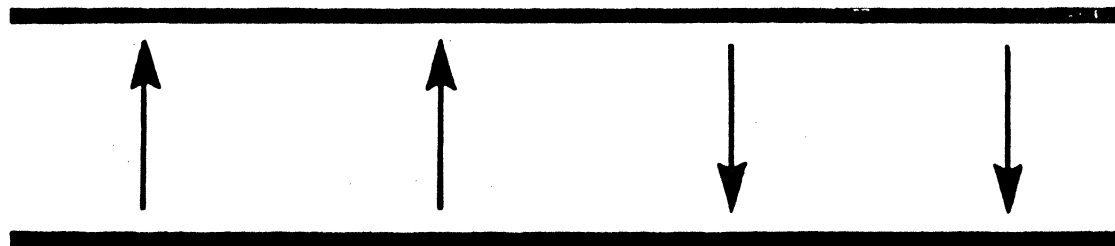


Media

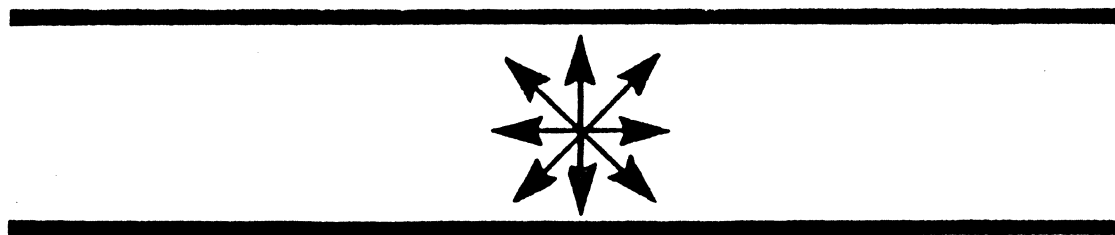
longitudinal



vertical



isotropic



DISK MEDIA

- Objective: Maximize
 - Linear density
 - Track density
 - Reliability
- Requirements
 - High resolution

$$P_{50} \cong \sqrt{g^2 + 4(a+d)(a+d+\delta)}$$

$$a \cong \frac{2 M_r \delta}{H_c}$$

- High S/N, S
 - Equalization
 - Servo PES
 - Off-track
- Low defect count
- High reliability
 - Corrosion
 - Wear

TECHNOLOGY TRENDS

- R/W

NRZ → FM → MFM → 2,7 CODE (350)

→ EQUALIZATION

→ ECC

- HEAD SLIDER

PRESSURIZED AIR → FLYING (MECHANICAL LOAD/UNLOAD)

↓
CONTACT (START/STOP) - LOW MASS

↓
SELF LOADING (NEGATIVE PRESSURE)

- ACTUATORS

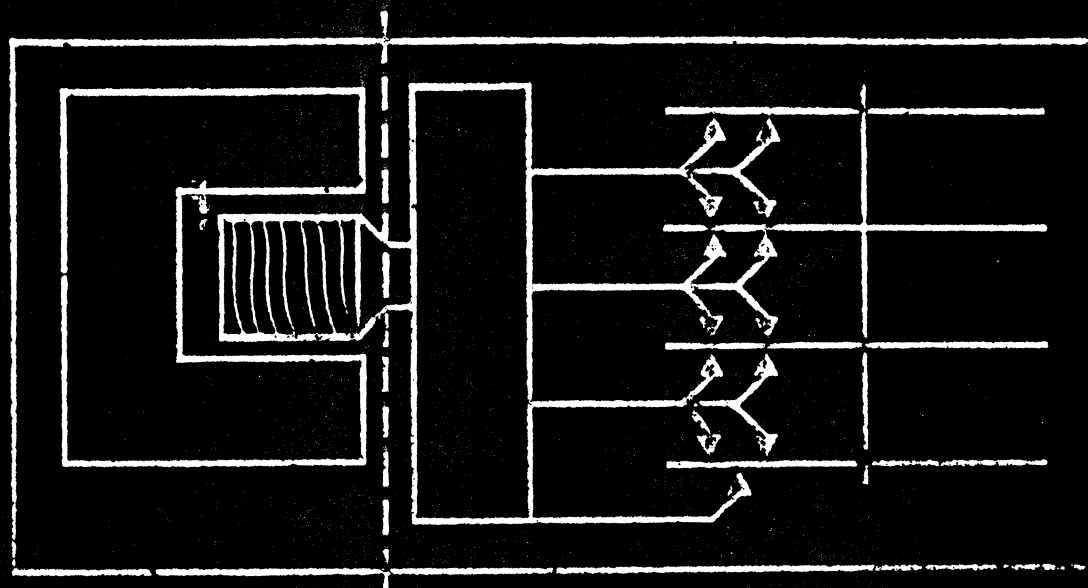
X-Y (RAMAC) → COMB → DUAL

↘
INDEPENDENT/DISK

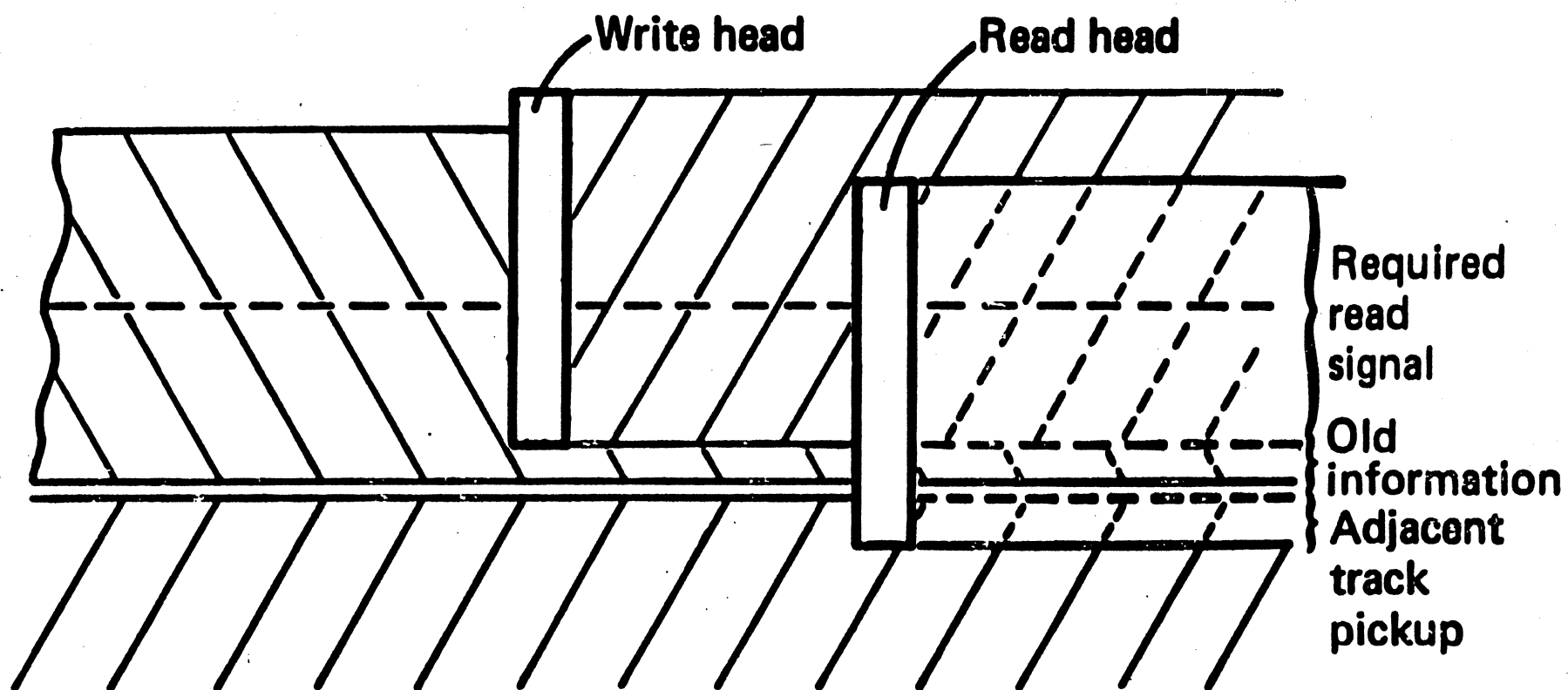
- DISK SIZE

→ DECREASE

Typical Head/Disk Assembly



Read head pickup of old/adjacent track information



Disk Storage Technology

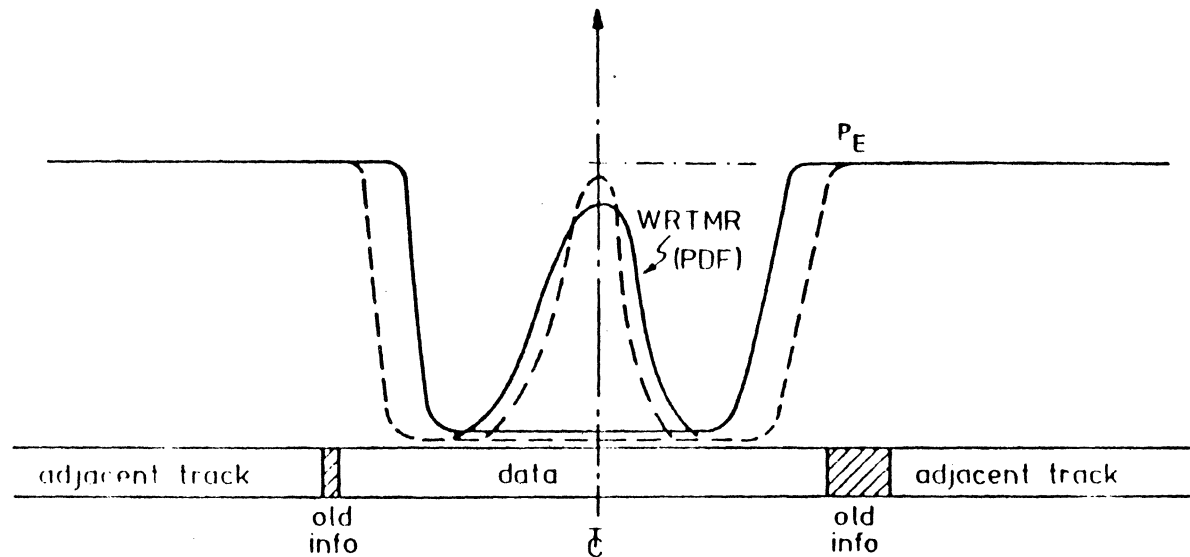


Figure 2 Radial section of disk showing 3 tracks

written track. This minimum OTC is shown as OTC_0 in Figure 1. It intersects the C_I - C_I curve at A_I and B_I .

In the absence of other considerations, we would define the interval A_I to B_I as the manufacturing tolerance and use P_I as the nominal design point. But the necessity of moving the head radially across the disk complicates the design process. At the inner diameter (ID), bit (flux change) density is the highest, requiring the best read capability.

The write capability, however, is less demanding because head-to-disk separation is the smallest, while the disk coating is the thinnest at the ID. We represent this by R_I - R_I , W_I - W_I , and C_I - C_I curves. OTC_0 intersects C_I - C_I curves at A_I and B_I . For outer diameter (OD), the ISI is small because of lower bit (flux change) density. Therefore, the OD demands much higher write capability because of thicker coating and larger head-to-disk separation. This is represented by R_O - R_O , W_O - W_O , and C_O - C_O curves. Note the relative location of ID and OD curves. Similar to ID, OTC intersects C_O - C_O at A_O and B_O . For ease of discussion, we have assumed that the

same OTC is required for ID and OD. In real life, this is not so, since track misregistration (TMR) at these two locations is, in fact, different.

Therefore, for a head to function properly at both ID and OD, the design margin is shrunk to A_O and B_I as indicated in the shaded area of Figure 1. The single-line design margin representation is true only for a given set of other recording parameters, such as disk coating thickness, orientation ratio, head-to-disk separation, read/write electronics, and so on. In fact, every one of these parameters has its own process variation and, therefore, is a distribution. When those distributions are considered, every curve in Figure 1 becomes a distribution. As a result, the design margin, A_O and B_I , is trimmed down more.

Error-rate prediction

The soft (correctable) error-rate goal for a disk file is chosen so that the time required for error recovery does not degrade throughput of data.

Most soft errors result from noise induced into the

head when it is misregistered with respect to the written track. Noise is any signal other than the desired data, including old data (old information) not entirely erased when the new data are written. The offset between head position while reading data and head position during the write operation is called "write-to-read track misregistration" (WRTMR). This offset is caused by uncorrected temperature, mechanical, and electronics tolerances.

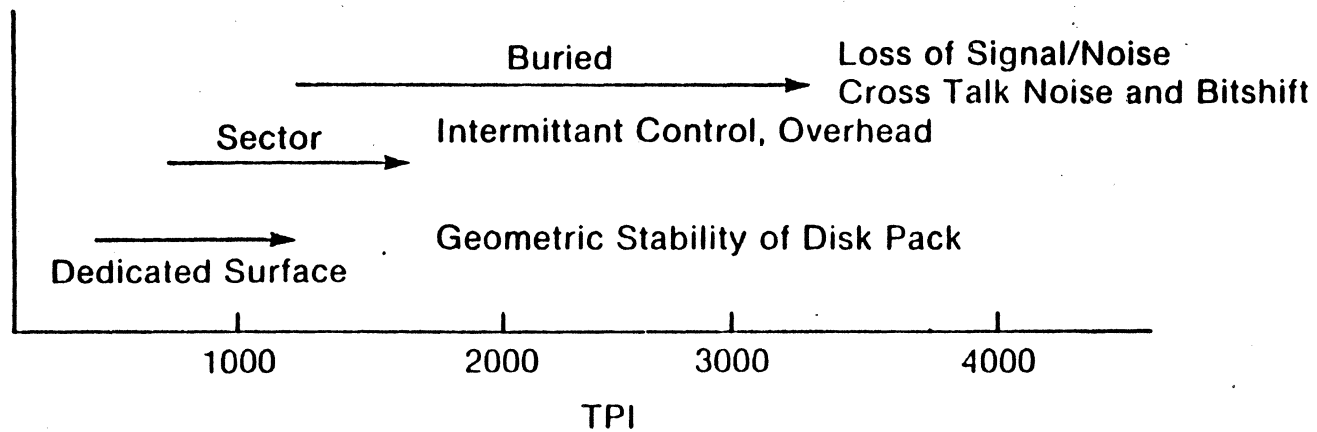
To estimate the soft-error rate of a head/disk/data-channel combination, we must know the probability of getting an error, P_E , at each given WRTMR and the probability of the head having that WRTMR (Figure 2). P_E is measured on a precision test stand with accurate head positioning by writing tracks as shown in Figure 2, then reading a sufficient number of times at different head positions to yield the P_E curve shown.

The probability distribution of WRTMR (Figure 2) is obtained by combining all measured component WRTMR distributions by a Monte Carlo method. Again employing Monte Carlo, we can randomly select a head position from the WRTMR distribution, determine the probability of a soft error, P_E , and finally find whether or not there was an error. By repeating this process thousands of times, an estimate of soft-error rate is obtained.

If the estimate does not meet the error-rate goal, we can either decrease the spread of the WRTMR distribution (reduce temperature, mechanical, and servoelectronics tolerances) or widen the P_E curve (alter head, disk, and data-channel design). Since off-track capability is a measure of the P_E curve width, we can relate this to Figure 1 if head geometry is to be altered for better off-track performance. Following any needed performance or TMR improvement, the error rate is estimated again and compared to the goal. During disk-file development, many cycles of TMR and performance alteration and error-rate estimation are analyzed.

The process of estimation is more complex than

Track Density in Magnetic Storage



- $V_s \propto \text{track width}$ — fundamental difference with optical storage
- At high FCPI adjacent track crosstalk rapidly increases bitshift beyond acceptable limit

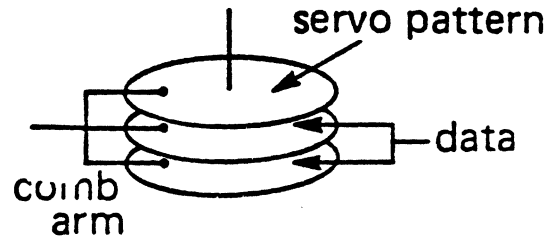
HEAD POSITIONING

Open Loop

low cost

Servo

- dedicated



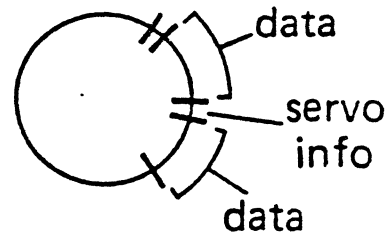
Issue - cascaded mechanical & thermal tolerances

- imbedded

(a) Sector

Issues - open loop when R/W

- real estate
- slew rate
- tolerance to disk defects



(b) Continuous

Issues - source of PES (position error signal)

- disk fabrication
- sensor
- servo while write

CONCEPTS - ACTUATOR TYPES

DEGREES OF FREEDOM

LINEAR ACTUATOR

RESONANCE

DIRECTLY EXCITED

INDIRECTLY EXCITED

DAMPING

ROTARY ACTUATOR

PIGGYBACK ACTUATORS

STEPPING MOTOR TYPES

LEAD SCREW

TAUT BAND

actuator, however, the effective mass at the head is the sum of the masses of the moving parts multiplied by the square of the ratio mass radius to head radius.

Thus, the resulting effective mass of a rotary actuator is likely to be lower than its equivalent linear actuator. A consequence of this is that the size and power of the motor required for a rotary actuator will be smaller.

This result satisfies two more of the basic actuator criteria. The disadvantage associated with rotary actuators is that of head yaw. This has at least two effects: 1) flying-height variation and 2) degraded mechanical stability.

In the case of the 62PC, the advantages of rotary actuators outweighed the disadvantages. This left the problems of yaw as perhaps the major mechanical problem to overcome during the development of the actuator.

Actuator description

The following description may be clarified by referring to the pictorial sketch of the actuator shown in Figure 1.

A total of seven arms are used to carry the twelve heads needed to access all surfaces of the disks. The five arms which are between disks carry two heads each and the two arms accessing the outer surfaces of the disk stack carry one head each. A single draw bolt is used to attach each head/arm assembly to the reference surfaces on the actuator hub. This permits removal of any one head/arm assembly from the final assembly without disturbing the other assemblies.

A voice coil attached to the opposite side of the actuator hub provides the necessary torque to drive the actuator. The voice coil comprises a multiturn coil wound onto a rectangular plastic former. This assembly is attached to the actuator hub. An

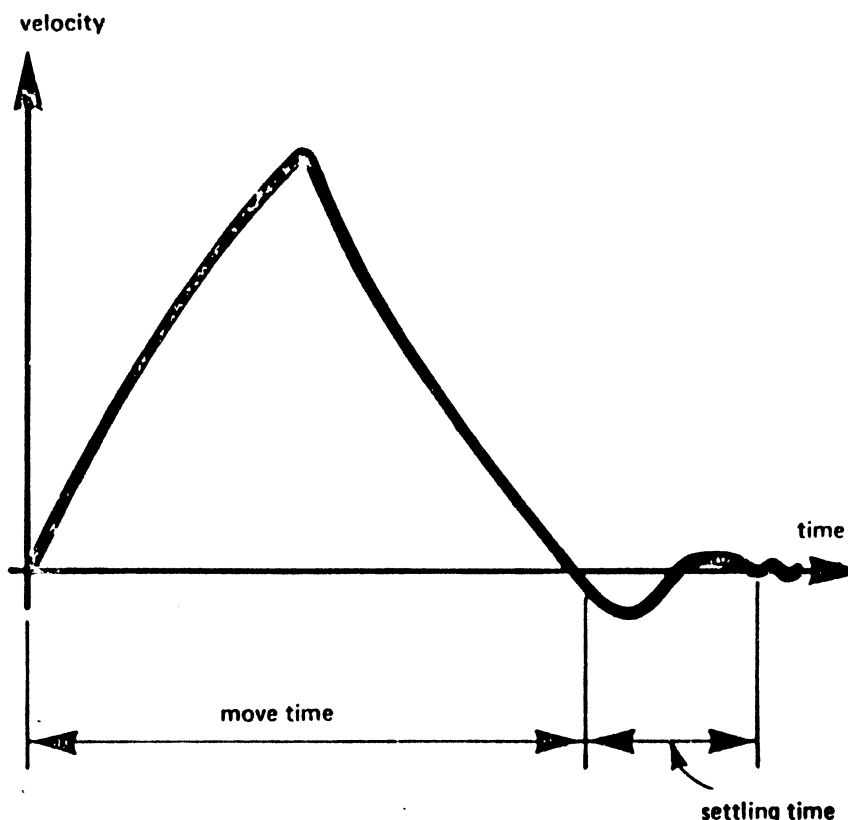


Figure 2 Typical velocity/time trace

E-shaped magnetic circuit provides two magnet gaps through which the radial surfaces of the coil pass. To minimize electrical interference to the data head signals, the preamp electronics are attached to the moving part of the actuator as close to the heads as the inertia penalty will permit. The casting which holds this electronics provides the vertical reference for the head/arm assemblies. Once the head signals are preamplified, they are passed to the data separator via a flat cable. The cable is formed in a C shape to minimize the torsional input to the actuator.

To limit the angular motion of the actuator, a pin attached to the hub casting is set between two preloaded spring assemblies. These springs are arranged to stop the actuator within a certain distance with the actuator travelling at a terminal velocity of the order of 27 rad/s. To ensure efficient use of the disk surface, this distance has been arranged to be the minimum that the resulting G forces at the head will allow.

The description so far has dealt with the moving part of the actuator. The swinging arm assembly is

Disk Storage Technology

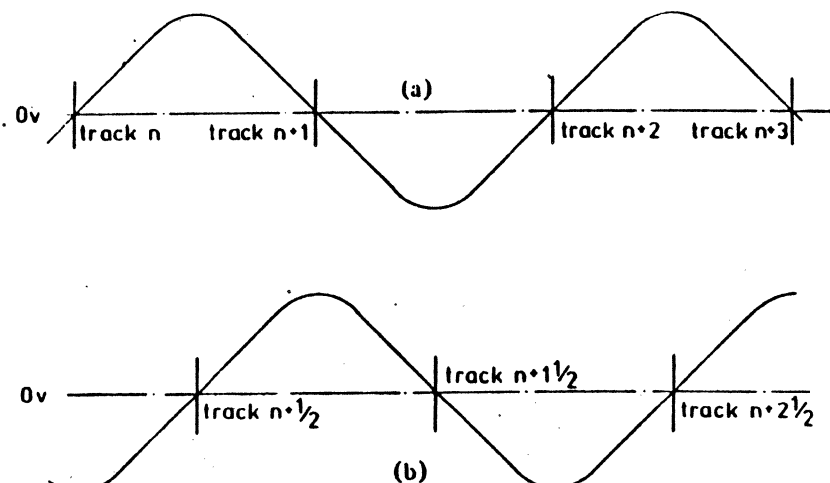


Figure 3 Data head signals: (a) conventional position error signal, (b) quadrature position error signal, (c) dedicated servo surface magnetization, (d) tribits at track n , (e) tribits at track $n+\frac{1}{2}$.

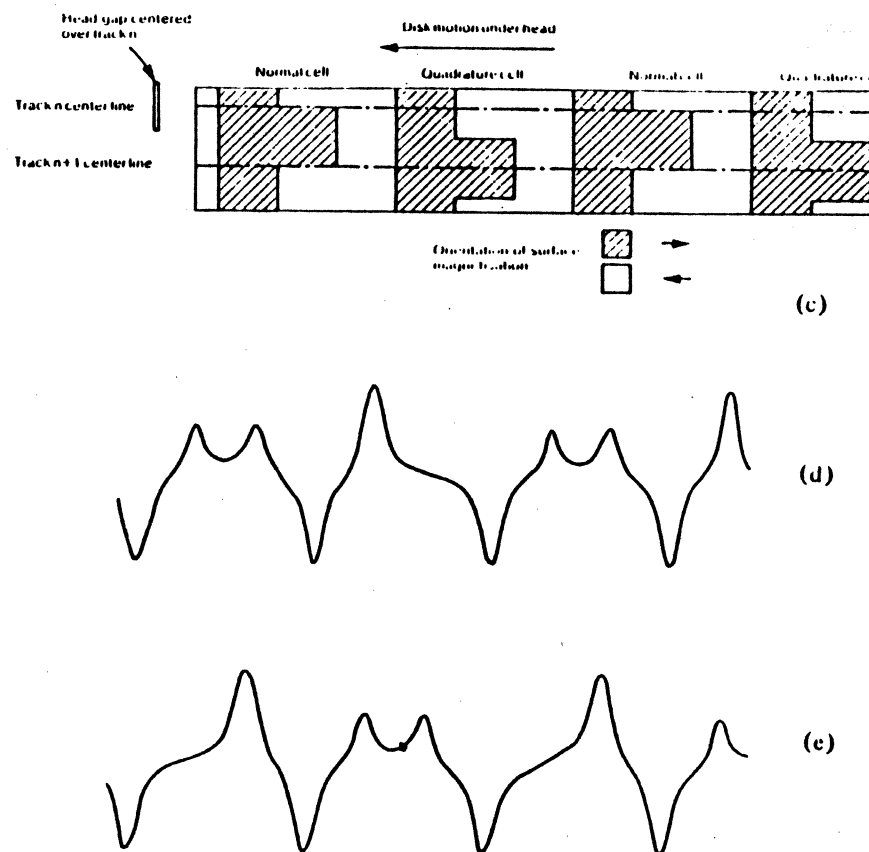


Figure 3(c, d, and e) explains the generation of normal and quadrature PES. The method uses the so-called tribit pattern, first used by IBM in the 3340 disk file. Figure 3c shows the surface magnetization for three tribit cells, which alternately provide normal and quadrature position information.

Figure 3(d and e) shows the head signal produced with the head centered over a normal track position, and half-way between two normal track positions. The principle is to find the difference between amounts of signal originating from each side of the

track center line. The value of the PES is therefore the difference between the positive pulse heights in the appropriate cell. Timing information is contained in the negative pulses.

The encoding technique for the data PES has to satisfy different constraints. These arise because the demodulator has to operate in regular bursts, short enough to minimize loss of data capacity, yet long enough to tolerate the effects of random short defects which occur in all magnetic disk coating. It must respond rapidly to changes in head-output amplitude which are likely to occur when different

heads are selected. Finally, the demodulated signal must define accurately the track center line.

The null pattern, shown in Figure 4, is used in 62PC to satisfy these constraints. In this pattern, magnetic transitions of opposite polarity appear simultaneously on either side of the track center line. When the head is on track, these two transitions result in equal pulses of opposite polarity, ideally cancelling to give no head output. In practice, it is difficult to maintain alignment between pairs of transitions on adjacent tracks so that the head reads them simultaneously.

Track Width

- (W = Track width) (s = signal output)
- $s \propto W e^{-\pi d(fci)}$
- $tpi \propto \frac{1}{W}$
- track density *versus* linear density

$$\text{bits/in}^2 \propto (fci)(tpi) \propto (fci) \times s \times e^{\pi d(fci)}$$

holding s constant, maximize bits/in² in terms of bpi and tpi

$$\frac{\partial(\text{bits/in}^2)}{\partial fci} = 0 \quad \text{or} \quad fci = \frac{1}{\pi d}$$

(ignoring noise) operate where a further increase in linear density causes a greater signal loss than an increase in track density would.

$$\text{Signal} \propto \frac{1}{t_{pi}}$$

$$\text{media noise} \propto \frac{1}{\sqrt{t_{pi}}}$$

SNR decreases 3 dB as
double tpi

recording band

$$\text{Capacity (C)} = 2 \pi r_i \cdot \text{bpi} \cdot (r_0 - r_i)$$

r_0 = outer radius recording band

r_i = inner radius recording band

or

$$C = 2 \pi \cdot (\text{bpi}) [r_0 r_i - r_i^2]$$

$$\frac{\partial C}{\partial r_i} = 0 = 2 \pi \cdot (\text{bpi}) [r_0 - 2r_i]$$

or

$$r_i = \frac{r_0}{2}$$

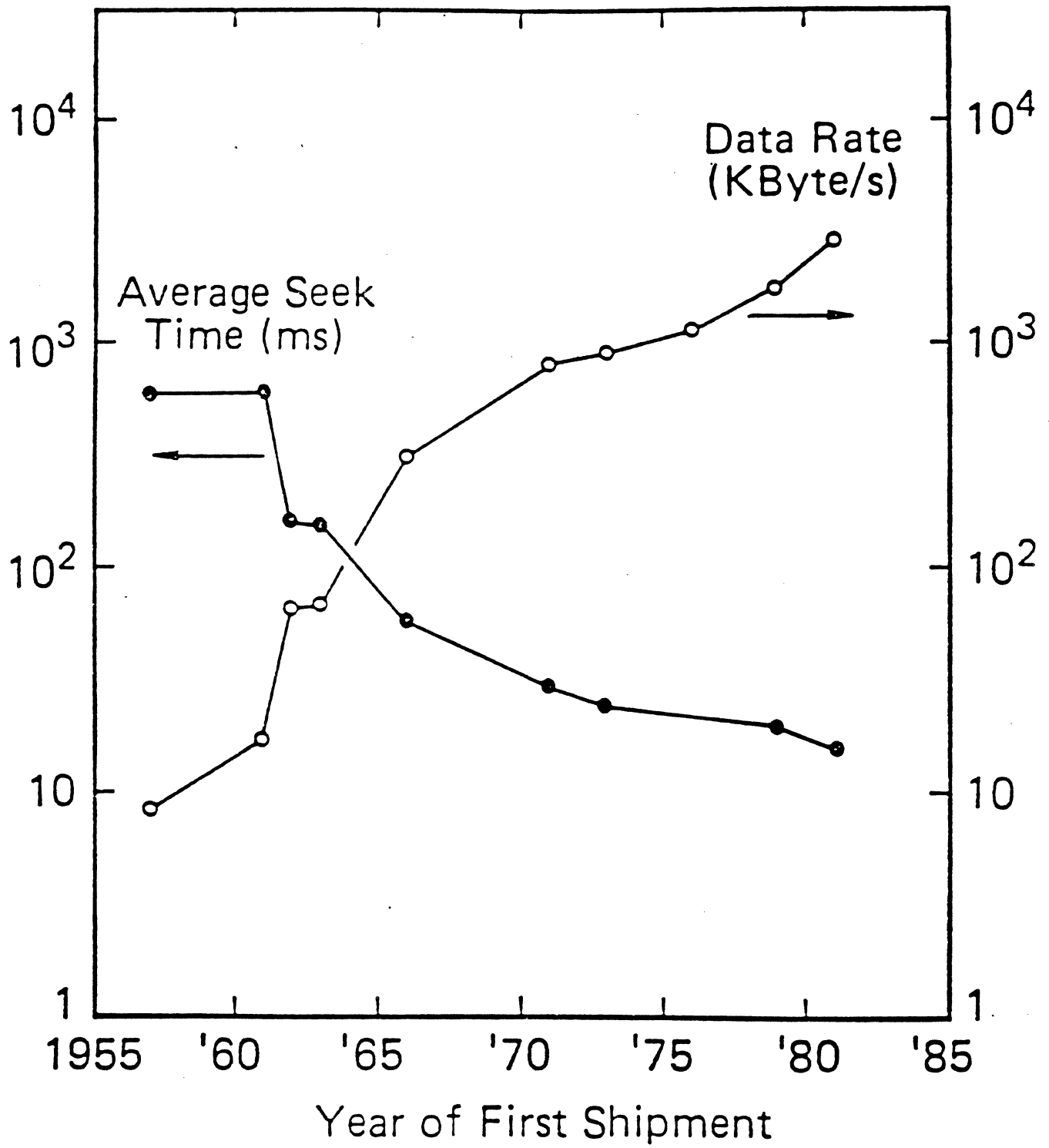


Table 1 Development of technologies in key areas of magnetic head and its air bearing support, disk substrate and its coating, head-positioning actuator, and read/write electronics.

Year of first ship Product	1957	1961	1962	1963	1966	1971	1973	1976	1979	1979	1981
	350	1405	1301	1311	2314	3330	3340	3350	3310	3370	3380
Recording density											
Areal density (Mb/in. ²)	0.002	0.009	0.026	0.051	0.22	0.78	1.69	3.07	3.8	7.8	>12
Linear bit density (bpi)	100	220	520	1025	2200	4040	5636	6425	8530	12134	15200
Track density (tpi)	20	40	50	**	100	192	300	478	450	635	>800
Key geometric parameters (micron.)											
Head-to-disk spacing	800	650	250	125	85	50	18	**	13	**	<13
Head gap length	1000	700	500	250	105	100	60	50	40	25	**
Medium thickness	1200	900	543	250	85	50	41	**	25	41	<25
Air bearing & magnetic element											
Bearing type	hydrostatic		hydrodynamic	**	**	**	**	**	**	**	**
Surface contour	flat	**	cylindrical	**	**	**	taper flat	**	**	**	**
Slider material	Al	**	stainless steel	**	ceramic	**	ferrite	**	**	ceramic	**
Core material	laminated mu-metal	**	**	**	ferrite	**	**	**	**	film	**
Slider/core bond	epoxy	**	**	**	**	glass	integral	**	**	deposited	**
Disk											
Diameter (in.)	24	**	**	14	**	**	**	**	8.3	14	**
Substrate thickness (in.)	0.100	**	**	0.050	**	0.075	**	**	**	**	>0.075
Rpm	1200	**	1800	1500	2400	3600	2964	3600	3125	2964	3620
Fixed/removable	fixed	**	**	removable pack	**	**	module	fixed	**	**	**
Data surfaces/spindle	100	**	**	10	20	19	6	15	11	12	15
Actuator											
Access geometry	x-y	**	linear radial	**	**	**	**	**	rotary	linear	**
Heads	2 heads/actuator	**	1 head/surface	**	**	**	2 heads/surface	**	1 h/s	2 h/s	**
Positioning	motor-clutch	**	hydraulic	**	**	**	voice coil motor	**	**	**	**
Final position	detent	**	**	**	**	**	servo surface	(+sector)	servo surface	**	**
Actuators/spindle (max. no.)	3	**	2	1	**	**	**	**	1	2	**
Avg. seek time (ms)	600	**	165	150	60	30	25	**	27	20	16
Read/write electronics											
Data rate (Kbytes/s)	8.8	17.5	68	69	312	806	885	1198	1031	1859	3000
Encoding	NRZI	**	**	**	2 f	mfm	**	**	mfm	2, 7	**
Detection	ampl	**	**	**	peak	delta	**	**	**	delta clip	**
Clocking	2 osc	**	clk trk	osc	vfo	**	**	**	**	**	**

**Same as in preceding column.

The evolution of the whole technology is given in the overview paper [3], and the progress in disk file manufacturing and in selected innovations in materials, processes, and testing is discussed in the paper by Mulvany and Thompson [4]. The present paper traces the development of each part of the technologies in four key areas:

- The development of the magnetic head and its air bearing support that provides the close spacing between the disk surface and read/write head necessary for high-density magnetic recording.
- The development of the disk substrate and its magnetic coating.
- The mechanical design aspects of the actuator that positions the read/write heads over concentric tracks of a rotating disk.
- The key innovations in logic and electronics required to read and write data reliably and accurately from a disk.

Much of this development has been based upon the work of many individuals who have created, over the past quarter of a century, a technological base that has permitted the improvement of almost four orders of magnitude in areal density shown in Table 1 and also enhancements in performance, function, and reliability. Two individuals in particular deserve mention because their influence was so pervasive through the early days of development. They certainly deserve credit for motivation and for active participation in many of the innovations to be discussed. They are R. B. Johnson, who had the vision that such a device was needed and could be built, and L. D. Stevens, who provided the engineering management that realized the first successful product [5].

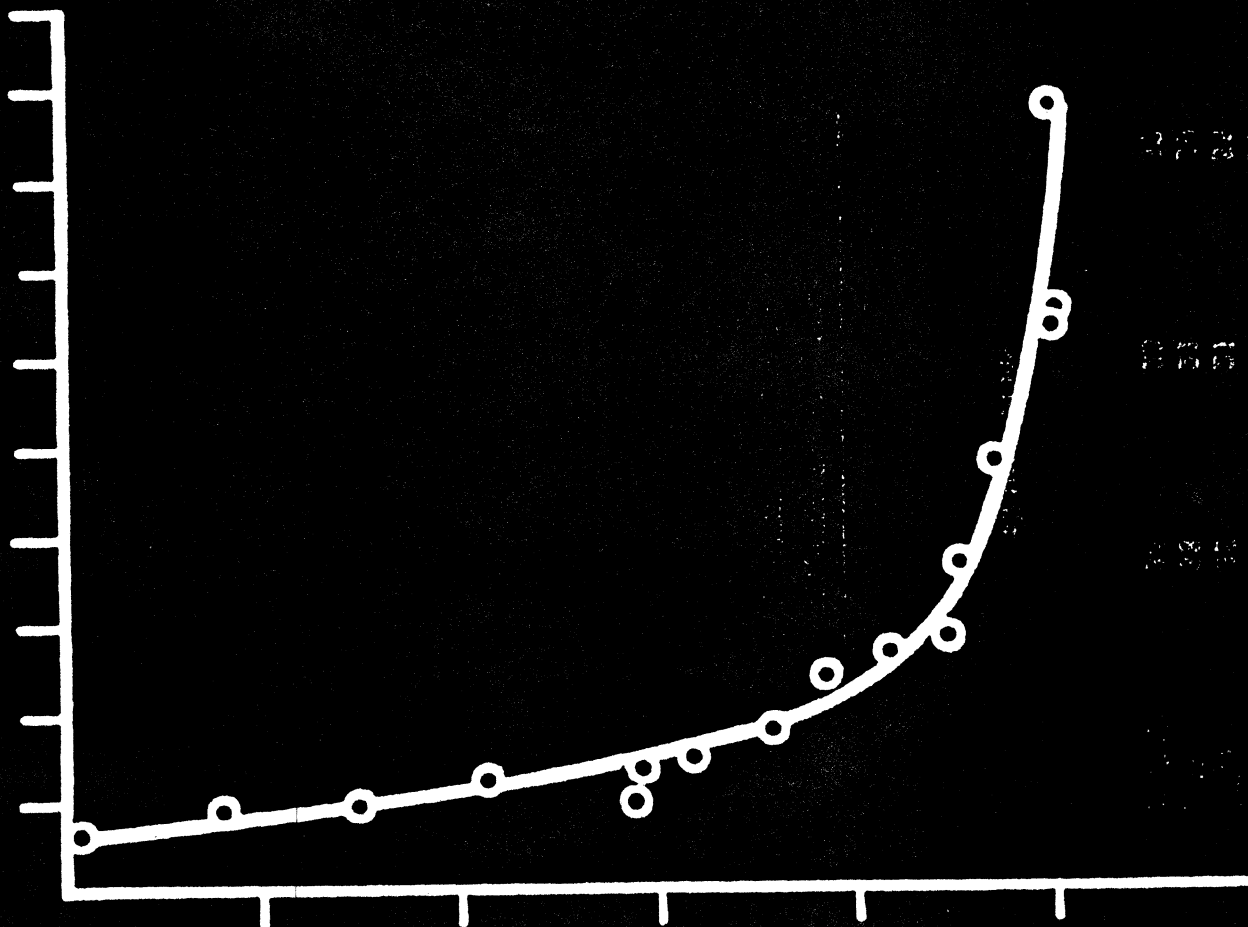
Air bearing spacing and magnetic heads

Film bearings, both self-acting and externally pressurized, have been in common use for over a hundred years.

MODEL CHARACTERISTICS

- * SYSTEM I/O RATE
- * CHANNEL THROUGHPUT CHARACTERISTICS
- * CACHE SIZE/HIT RATIO
- * CONTROL UNIT PATHING
- * DASD CHARACTERISTICS
 - SEEK TIME
 - DATA TRANSFER TIME
 - NUMBER OF ACTUATORS

I/O Response Time

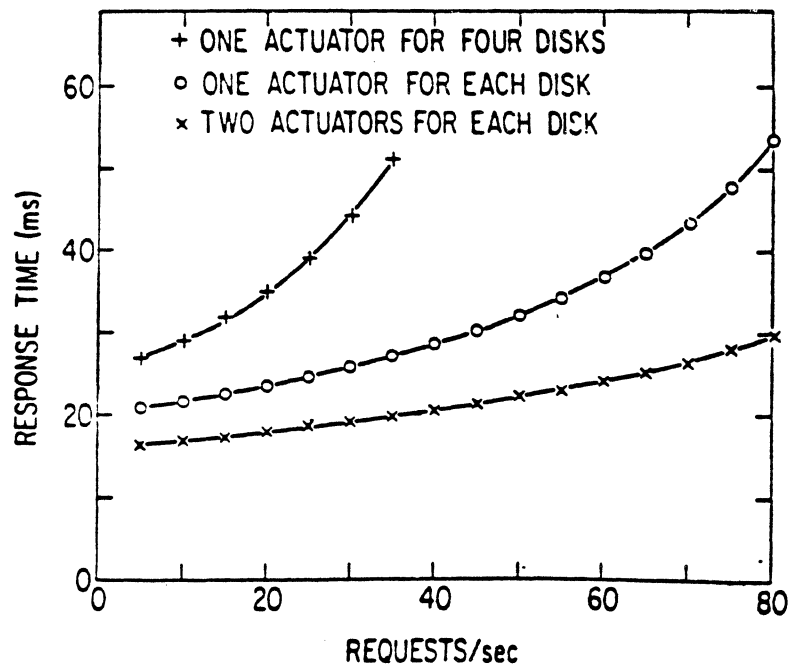


System I/O Operations per Second

Response Times for Non-Paging Disk Storage

System	Service Time	Queuing Time	Total Response Time
TSO	32	33	65
TSO	35	16	51
TSO	35	21	56
IMS	38	21	59
BATCH	34	23	57

all times in ms



IBM 3850

The IBM 3850, introduced in 1975, is also a magnetic tape-based system. However, in place of reels it uses tape cartridges which are 3.5" long x 2" in diameter and contain up to 4×10^8 bits. They are stored in a vertical honeycomb of hexagonal cells. As many as 4720 cartridges may be stored in a single 3850. An automated accessing device picks the desired cartridge and presents it to an auto loading helical scan tape drive called a Data Recording Device (DRD).

The media characteristics are shown in Figure 7. The data is staged from

Magnetic Tape Cartridge
2.7" wide tape, 770" long
6250 bpi, 67 tpi
50.4 M Bytes/cartridge
\$33/cartridge
874 KB/sec:369 KB/sec
100 ips search

Figure 7: IBM 3850 Media

the Data Recording Device to an IBM 3330 or 3350 disk and then accessed from the disk as required. Some of the configurations for the 3850 are shown in Figure 8. The A models have one controller and the B models have two controllers.

Models	Capacity
A1, B1	35 G Bytes
A2, B2	102 G Bytes
A3, B3	169 G Bytes
A4, B4	236 G Bytes

Figure 8: IBM 3850

The capacity ranges from 2.8×10^{11} bits to 2×10^{12} bits. The majority of 3850 users have the 102 G Byte capacity system and employ it in a multi-host environment. A list of specifications for the 3850 are given in Figure 9. The cost for such a system is from \$.75M to \$1.8M.

MECHANICAL

Height: 72", Width: 30", Length: 180"-360"

Heat Dissipation: 19,500 - 41,500 BTU/hr

Weight: 4250 - 10,310 lbs

ELECTRICAL

208 Volts, 3 phase, 30-60 Amps

PERFORMANCE

Access time: 15 sec

Up to 500 cartridge mounts/hour

SOFTWARE

MVS, MVSXA, VS/1

Figure 9: IBM 3850 Specifications

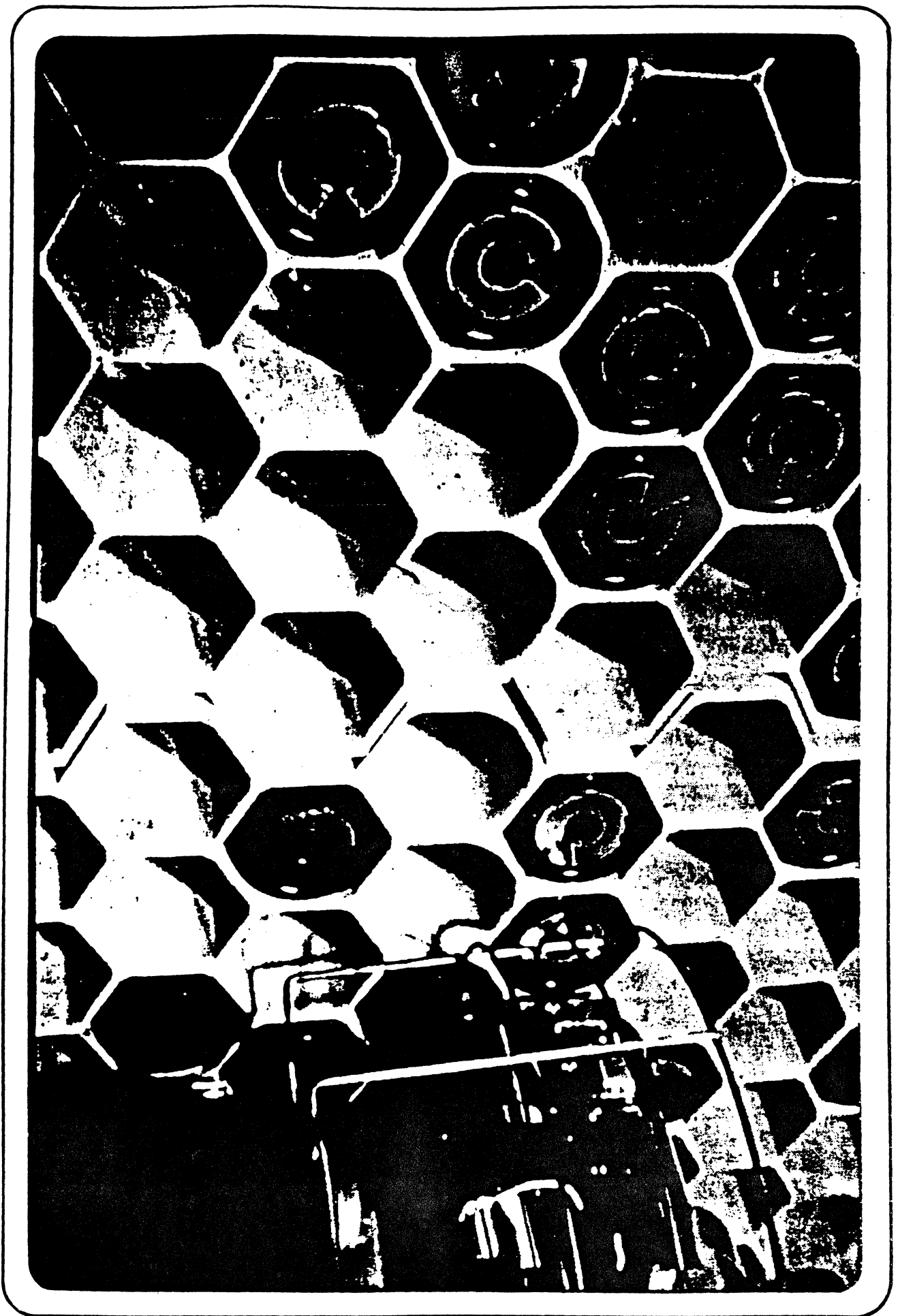
MASSTOR M860

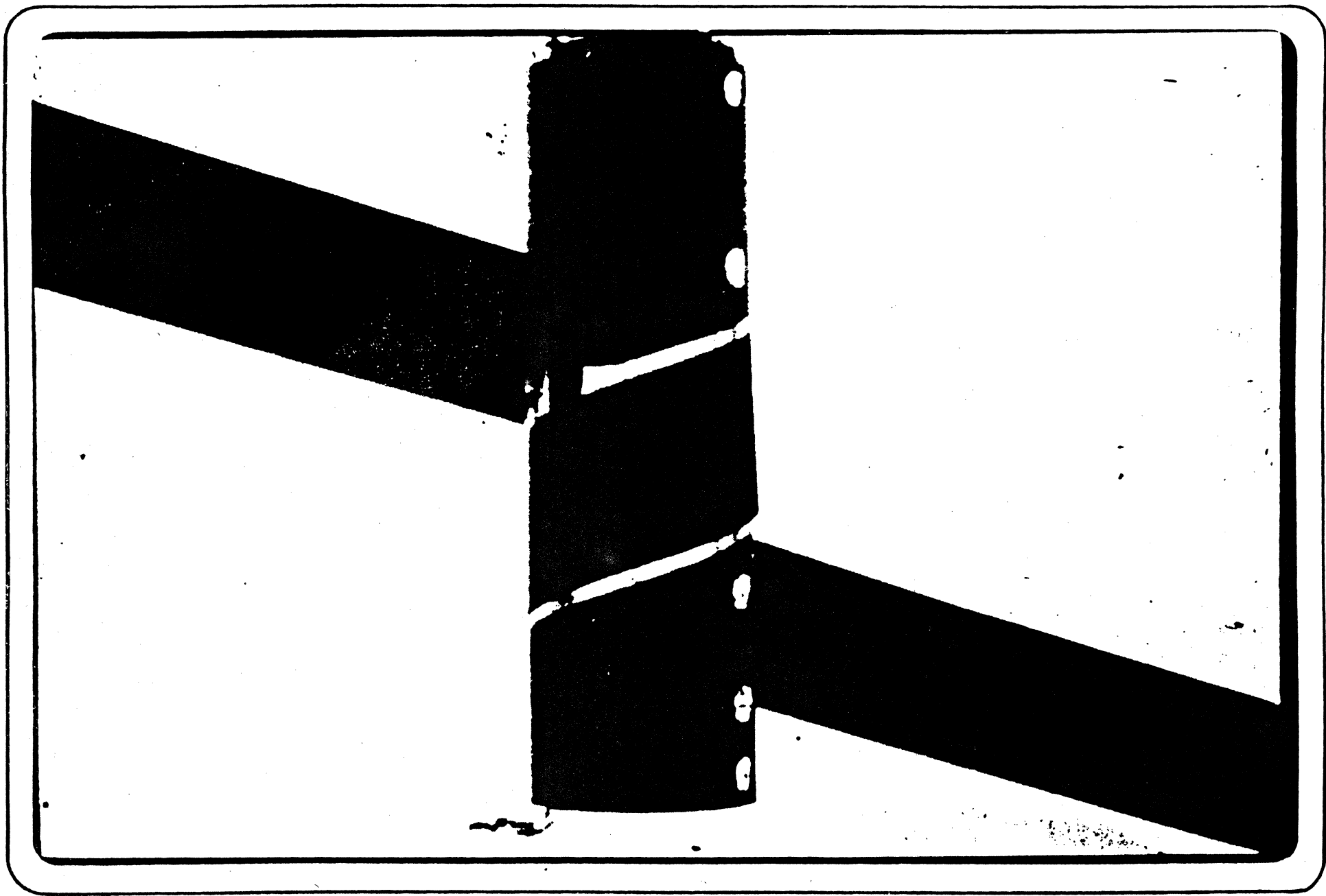
A new entry this year in the mass storage field is the MASSTOR M860. An earlier model, the M850, is similar in design to the IBM 3850; however, the M860 is a departure in both the mechanical accessing mechanism and the storage density on the tapes. Although the M860 uses the same IBM cartridge, it achieves three times the storage density. The mechanical hardware is built by Nippon Peripherals, Incorporated. The M860 media characteristics are shown in Figure 10.

Magnetic Tape Cartridge
2.7" wide tapes, 770" long
10,000 bpi, 130 tpi
175 M Bytes/cartridge
\$33/cartridge
1075 K Bytes:750 K Bytes/sec
100 - 200 ips search

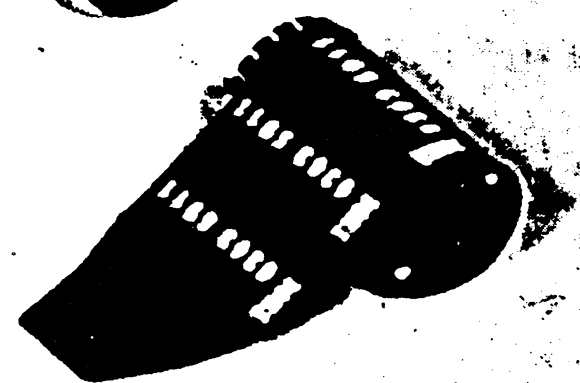
Figure 10: MASSTOR M860 Media

The M860 System is modular in blocks of 55 B Bytes and can be expanded with up to 8 modules or 440 B Bytes. Each module contains its own cartridge accessing arm. The System specifi-





Tape Medium

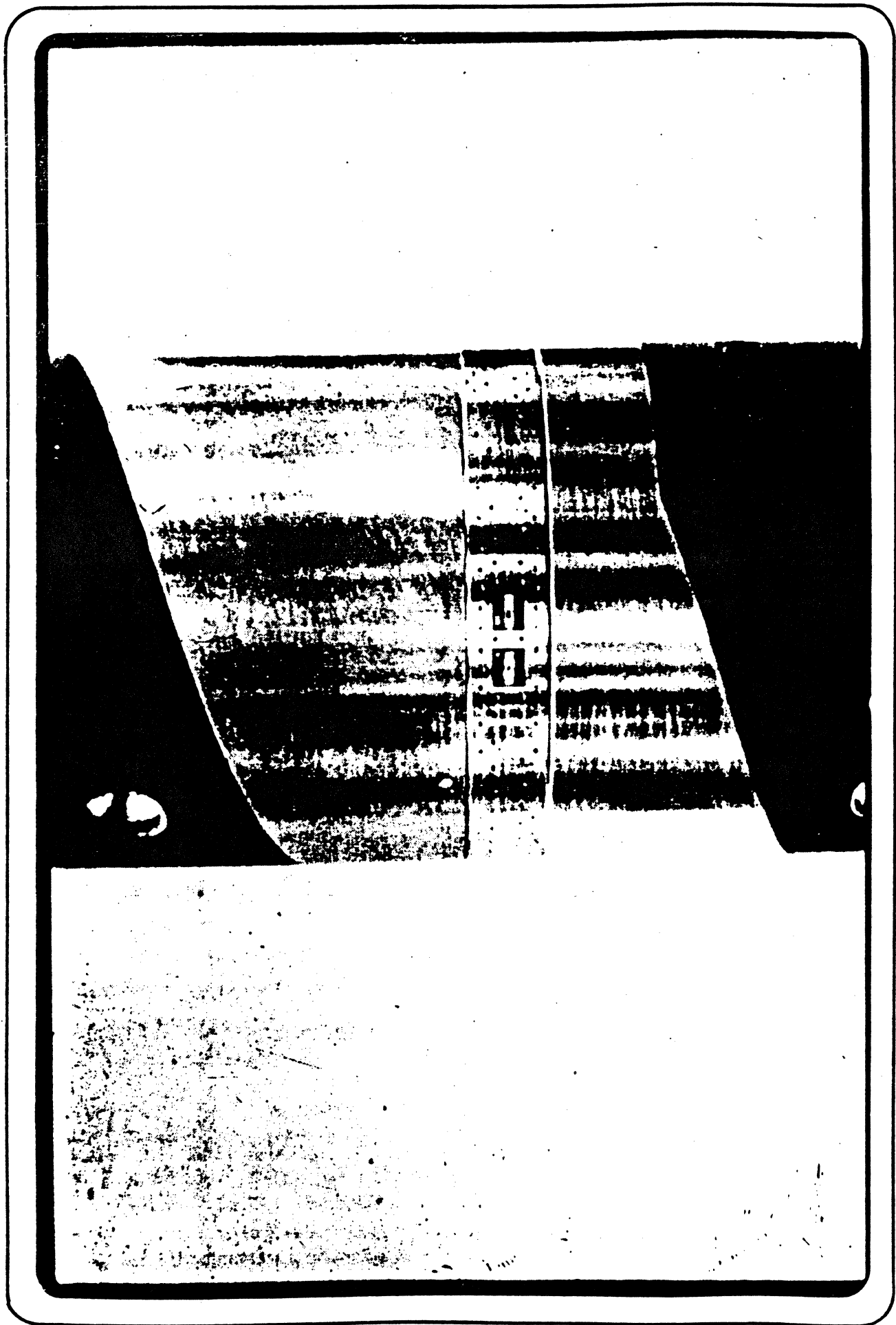


Cartridge

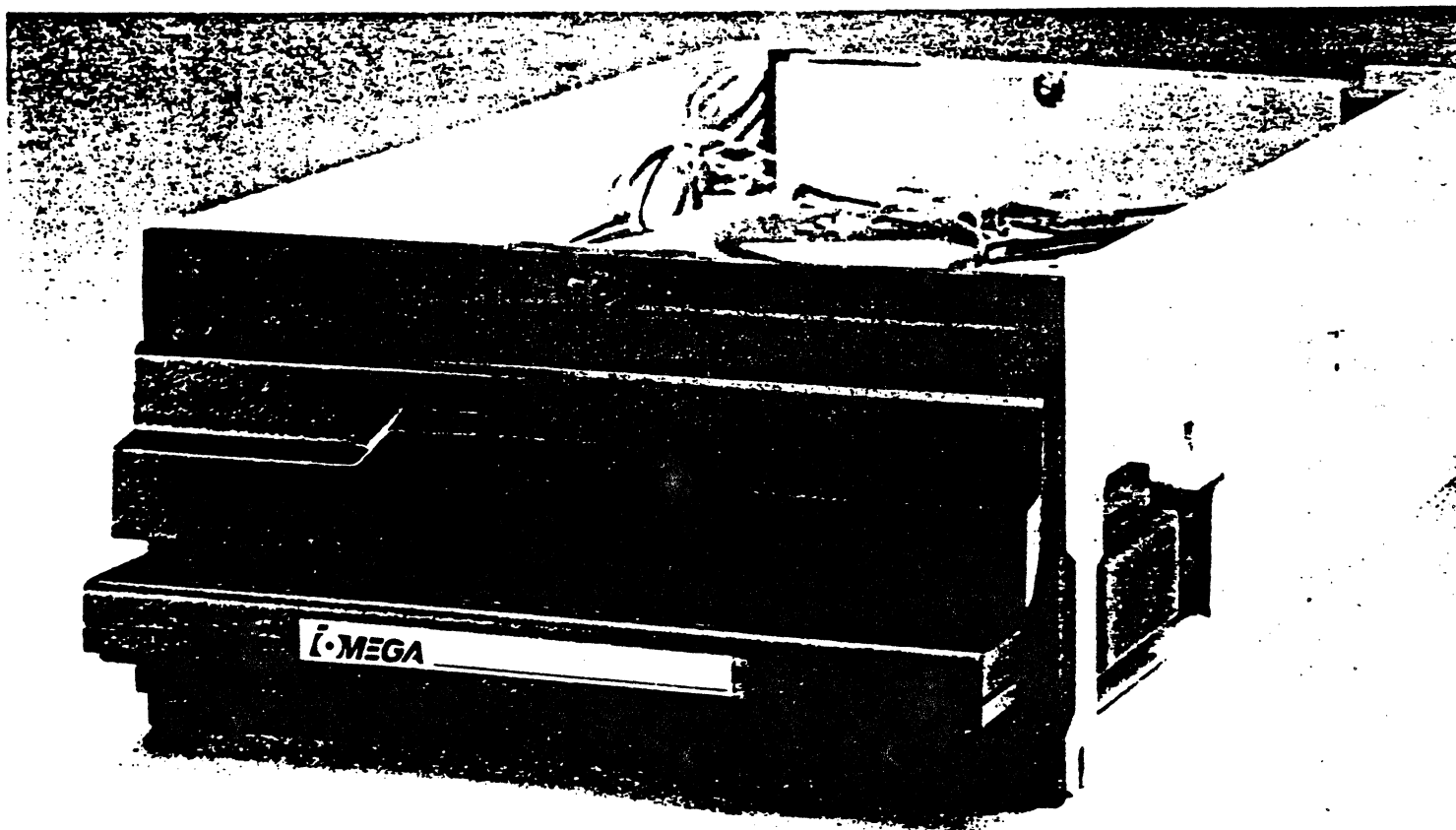
Length $\cong$ 8.7 cm (4 in.)
Dia. $\cong$ 4.7 cm (2 in.)

Tape

Width $\cong$ 6.8 cm (3 in.)
Length $\cong$ 16.94 m (770 in.)
Usage Length $\cong$ 14.67 m (667 in.)
Data Bytes = 4,096 per stripe
Capacity = 50.4 Mega Byte
Volume = 1/2 Mass Storage Volume



•MEGA™



Alpha-10™

Highest performance and reliability of any Removable Disk Drive • Lowest-cost 10 megabyte Disk Cartridge •

More resistant to shock and vibration than any other

Fixed or Removable Disk Drive • More resistant to contamination than any other Removable Disk Drive •

Fastest start/stop (cartridge replacement) time of any high performance Disk Drive • Only Disk Cartridge

Subsystem (drive, controller and cartridge) to dimensionally conform to the diskette standard (size and mounting)

SUBSYSTEM SPECIFICATIONS

CAPACITY

USER AVAILABLE (FORMATTED) CAPACITY, BYTES PER	
Drive	10,027,008
Cartridge	10,027,008
Surface	10,027,008
Track	32,768
Sector	512
Record	256

BYTES PER FORMATTED CARTRIDGE

User Available	10,027,008
Spare	
• For Field Flagging, Min	873,472
• For Factory Flagging, Max	51,200
Overhead	3,155,280
Total	14,106,960

PERFORMANCE

DATA TRANSFER RATE

Drive to Controller	1.13 Mbytes/sec
Controller to Host	
• Single Record Burst (256 bytes)	1.13 Mbytes/sec
• Contiguous Records (same track)	896 Kbytes/sec

SEEK TIME (INCLUDES SETTLING TIME)

Minimum	10 msec
Average	35 msec
Maximum	75 msec

LATENCY (AVERAGE ROTATIONAL DELAY)

Spindle Speed	1500 rpm $\pm$ 0.5%
---------------------	---------------------

TRACK-TO-TRACK ACCESS TIME

Consecutive Records Over Track Boundary	10.3 msec
---	-----------

START/STOP TIME (AVERAGE)

.....	3/6 sec
-------	---------

RELIABILITY

ERROR RATES

Data	
• Recoverable	10^{10} bits
• Non-Recoverable at Host Interface with ECC	$>10^{12}$ bits
Seek	10^6 seeks

MEAN TIME BETWEEN FAILURES

Subsystem	8,000 hr
-----------------	----------

MEAN TIME TO REPAIR

.....	0.5 hr
-------	--------

SERVICE LIFE

.....	5 years
-------	---------

PREVENTIVE MAINTENANCE

.....	none
-------	------

CARTRIDGE INSERTION/REMOVAL CYCLES, MAX ..

.....	5,000
-------	-------

ENVIRONMENT

OPERATING

Temperature	10° to 46°C ... 50° to 115°F
-------------------	------------------------------

Relative Humidity	
-------------------------	--

(Noncondens:	10 to 80%
--------------------	-----------

Maximum Wet Bulb	26.6°C	80°F
Maximum Temperature Gradient	12°C/hr	22°F/hr
Altitude	to 3048 m	10,000 ft
Shock *	3 g's for 20 msec	
Vibration *	0.85 g's at 5-17 Hz	
	0.25 g's at 17-500 Hz	

	Particle size (micron)	Particles/M ³
Air Cleanliness	< 1.0	4 X 10 ⁷
	< 1.5	4 X 10 ⁶
	< 5.0	4 X 10 ⁵

STORAGE AND SHIPPING

	Storage (6 mo)	Shipping (96 hr)
Temperature		
• Drive and Controller	-22° to 52°C	-40° to 60°C
	-8° to 126°F	-40° to 140°F
• Cartridge	10° to 52°C	-40° to 52°C
	50° to 126°F	-40° to 126°F
Relative Humidity (noncondensing)	10 to 90%	
Shock * (four drops)	40 g's for 15 msec	
Vibration *	1.3 g's at 5-27 Hz	
	2 g's at 27-60 Hz	
	5 g's at 60-500 Hz	

POWER

VOLTAGE

Voltage (vdc)	Max Current (amps)	
	Continuous	**Instantaneous
5 $\pm$ 5%	3.8	4.0
12 $\pm$ 5%	1.0	3.0
12 $\pm$ 5%	2.0	3.0

POWER (MAX CONTINUOUS POWER CONSUMPTION IN WATTS)

First Drive With Controller	55
Each Additional Drive	10

PHYSICAL

DIMENSIONS

	Height	Width	Depth
Drive ***	4.50 in.	8.54 in.	14.09 in.
	114.30 mm ...	217.00 mm ...	358.00 mm
Front Panel,	4.50 in.	8.54 in.	0.24 in.
Without Bezel	114.30 mm ...	217.00 mm ...	6.00 mm
Bezel	1.83 in.	8.54 in.	0.52 in.
	46.50 mm ...	217.00 mm ...	13.25 mm
Cartridge	0.71 in.	8.23 in.	11.02 in.
	18.00 mm ...	209.00 mm ...	280.00 mm

	Diameter	Thickness
Flexible Disk	7.8 in.	0.003 in.
	199.0 mm	0.08 mm

MOUNTING

Drive

- Same As Industry Standard Diskette Drive (SA 801R)
- ### Controller
- Mounted Within Drive
- ### Cartridge
- No Protrusion Beyond Drive Bezel

WEIGHT

First Drive With Controller \	13.0 lb	5.90 kg
Drive With Protective Panels	12.4 lb	5.62 kg
Cartridge	1.3 lb	0.59 kg

ORGANIZATION

CONFIGURATION

Drives Per Controller	1 to 4
Cartridges Per Drive	1
Flexible Disks Per Cartridge	1
Recording Surfaces Per Flexible Disk	1
Formatted (user-available) Tracks per Surface	306
Formatted (user-available) Sectors per Track	64
Records Per Sector	2
Bytes Per Record	256

FORMATS

Surface	
• Outer Guard Bands	16
• Data	306
• Z-Track	1
• Spares, for Field Flagging	4
• Inner Guard Bands	16
Total Tracks	343

Track

• Data	64
• ECC	1
• Spares, for Factory and Field Flagging	5
Total Sectors	70

Sector

• Data (two records of 256 bytes each)	512
• Servo	27
• CRC	6
• ID	4
• VFO, Sync, and PAD	99
Total Bytes	648

RECORDING

ENCODING METHOD	RLLC
RECORDING DENSITY	24,000 bpi
FLUX DENSITY	18,000 fci
TRACK DENSITY	300 tpi
AREAL DENSITY	7.2 Mbits/in. ²

* Each specified shock and vibration level is applied separately to each of the three mutually perpendicular planes of the drive; the planes being defined as the top, front, and side.

** Instantaneous values should be used in determining minimum power supply requirements.

*** Without front panel and with and with controller.

Longitudinal vs. Vertical vs. Isotropic

Read

Same loss factors apply

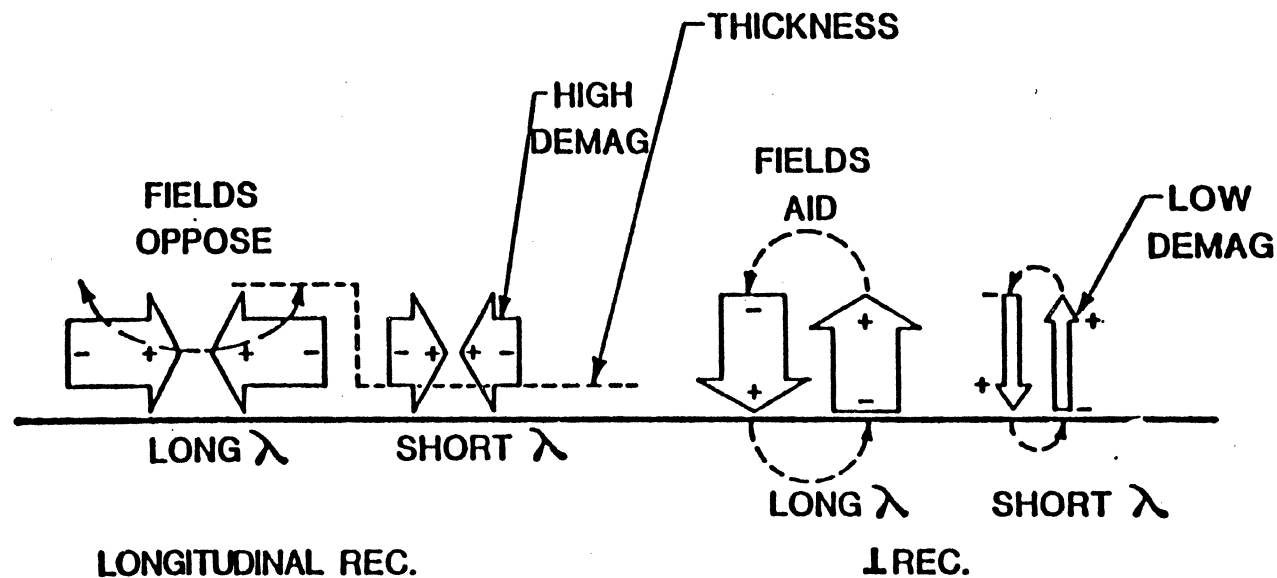
Write

Transition width set by both

Head field gradient $\langle \rangle$ medium demagnetization

ADVANTAGES OF $\perp$ RECORDING

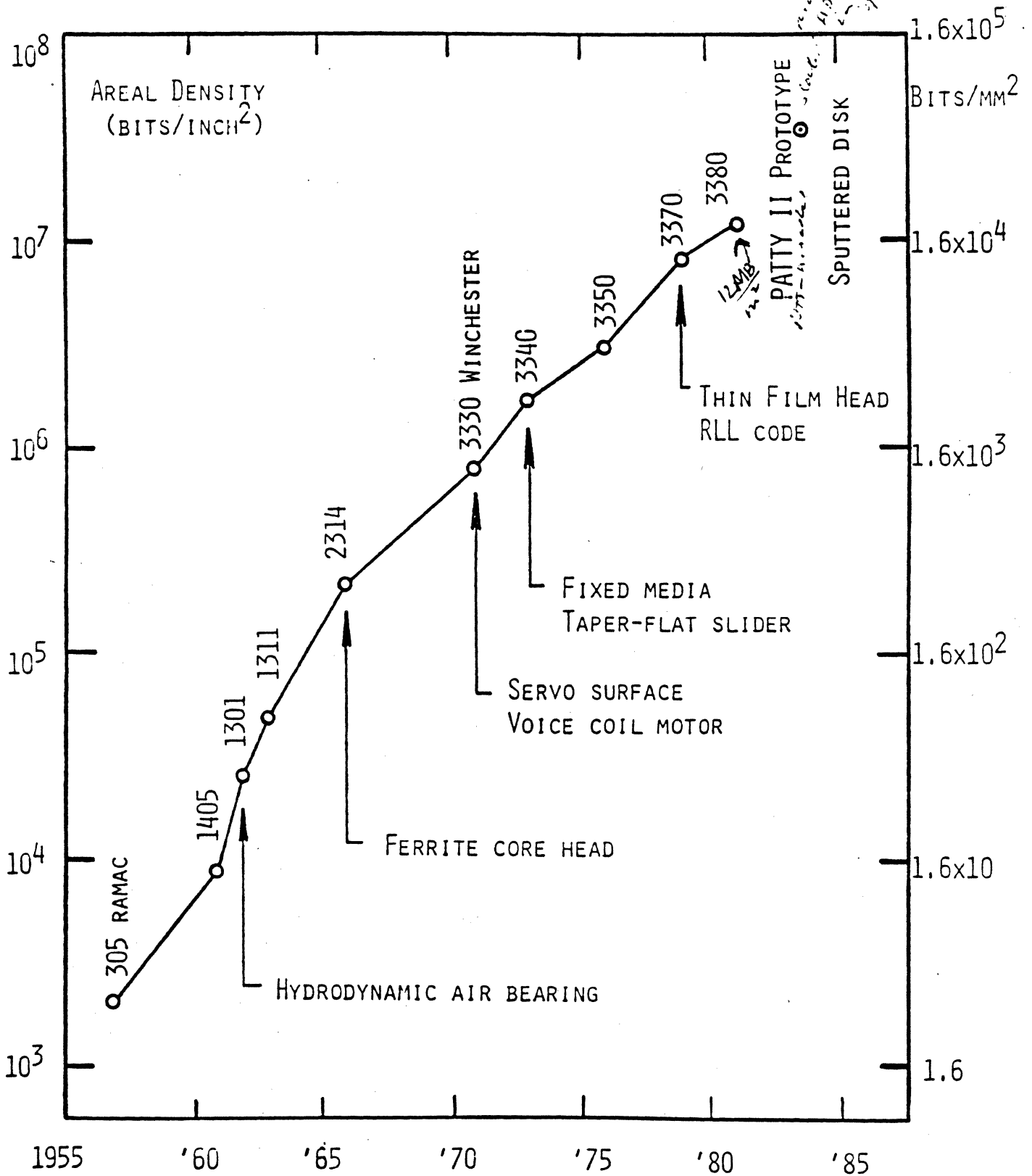
- DEMAG REDUCES AS λ GETS SHORTER
- TRANSITION LENGTH ≈ 0 (ADJACENT TRANSITIONS AID)
- THICK MEDIUM OK



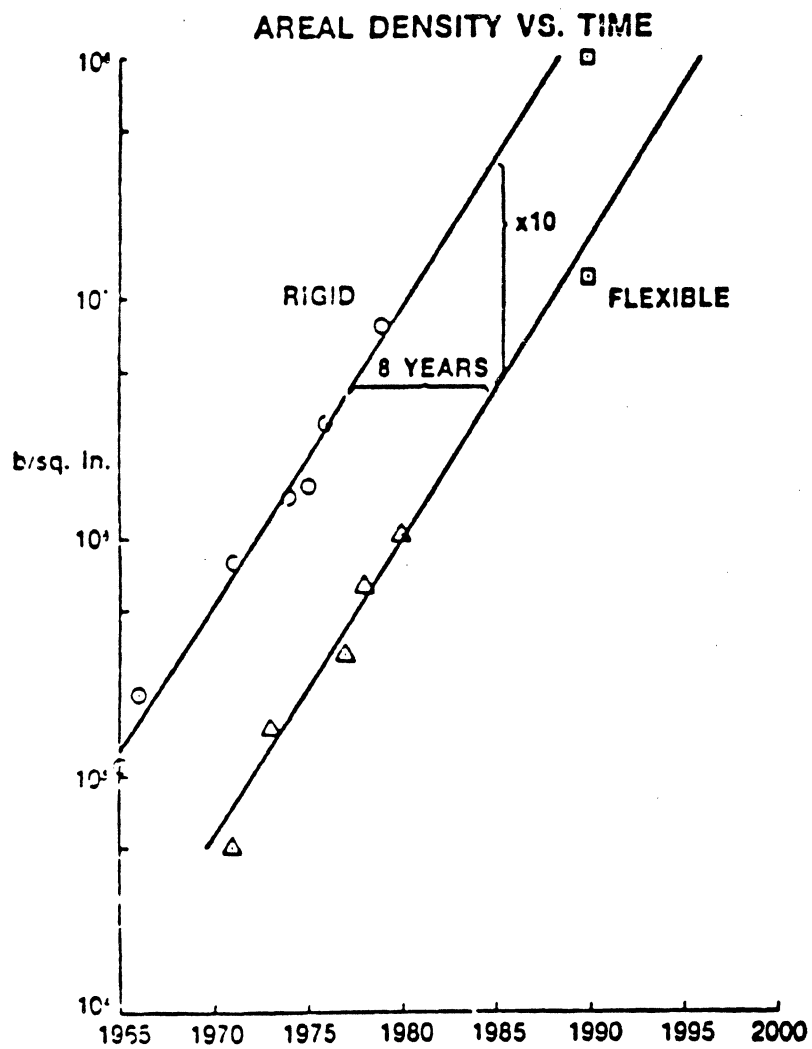
Fundamental Noise Limits

- **Johnson (thermal) noise from real (resistive) impedance of the magnetic head**
- **Preamplifier input noise (limited by Silicon technology)**
- **Magnetic particle or domain distribution**

3000 3 B A
 12/1/64
 11/1/64
 10/1/64
 9/1/64
 8/1/64
 7/1/64
 6/1/64
 5/1/64
 4/1/64
 3/1/64
 2/1/64
 1/1/64



STORAGE DENSITY OF MAGNETIC DISK DRIVES.



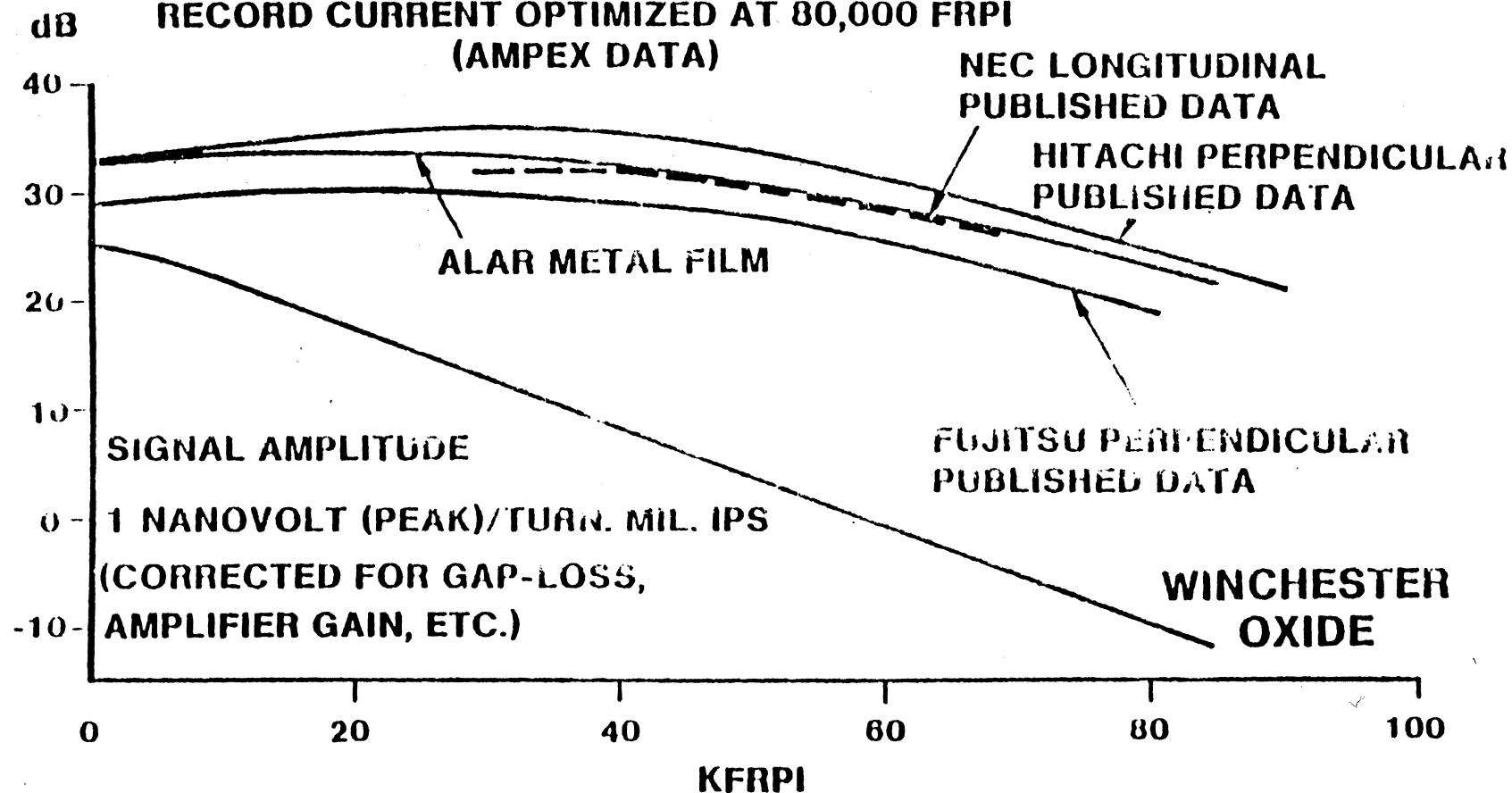
HIGH DENSITY COMPARISON OF RECORDING MEDIA

MANGANESE-ZINC FERRITE HEAD, $g = 12\mu$ "

FLYING HEIGHT $\leq 4\mu$ "

RELATIVE VELOCITY = 500 IPS

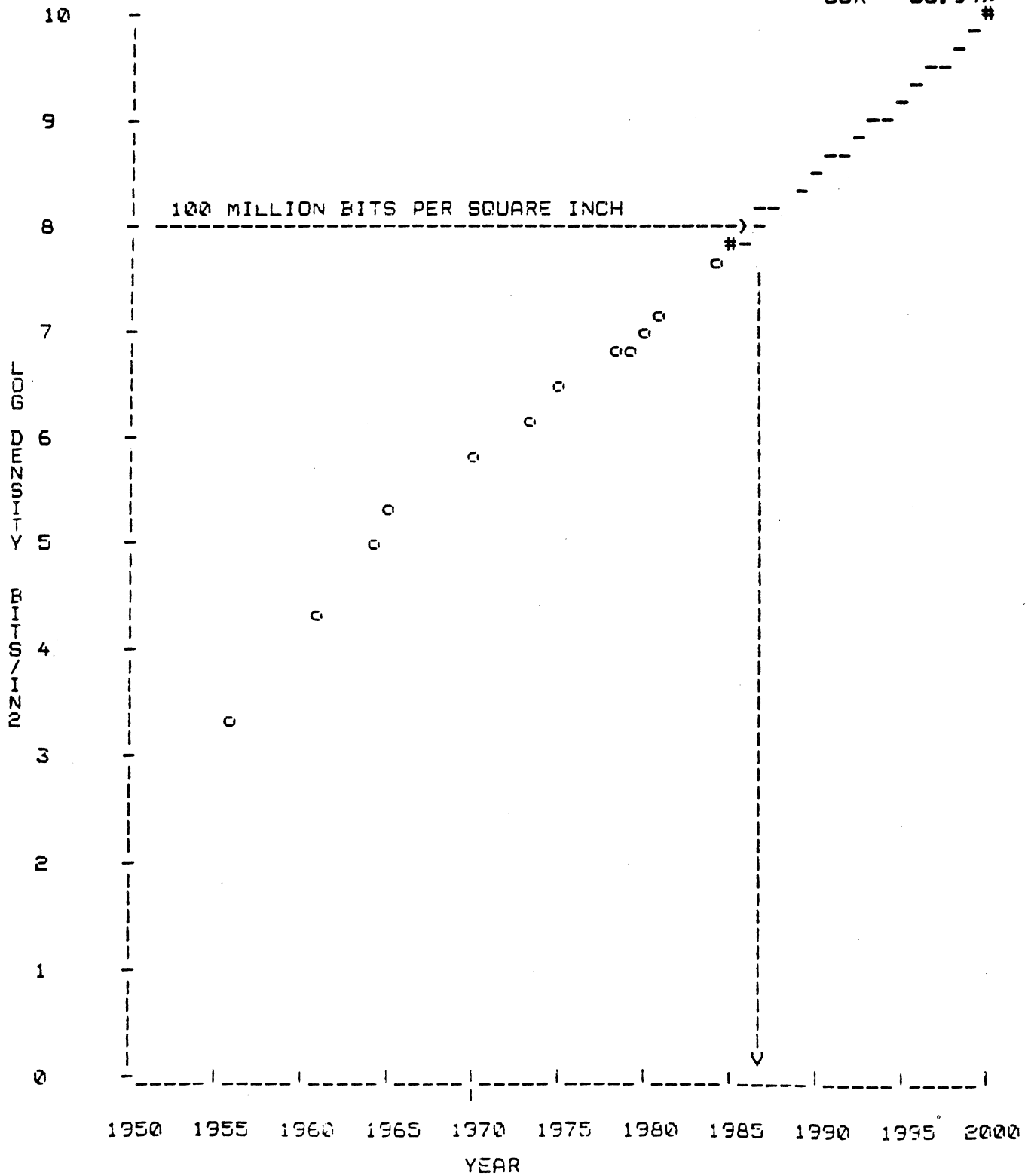
RECORD CURRENT OPTIMIZED AT 80,000 FRPI
(AMPEX DATA)



DISK STORAGE DENSITY

^o DISK DRIVE
PROJECTED TREND LINE

CGR = 38.94%



MAGNETIC STORAGE DEVICES

LINEAR {thin film processes} : TRACK {servo on data}

DENSITY ----->>

Volumetric efficiency : Low cost

PARALLEL HEAD ARRAYS

DATA RATE ----->>

Image storage

MULTIPLE ACTUATORS

ACCESS TIME ----->>

Storage subsystems

is. Caus. by movement
the one reading is 100%
from the 100% 100%

QUESTIONS IN MAGNETIC RECORDING

OVERWRITE

- IMPACT ON THIN FILM VERSUS PARTICULATE DISK
- IMPACT ON HEAD DESIGN

TRACK SEEK AND SERVOING

SOURCE OF PES

- IMPACT ON CHOICE OF MEDIA

PACK WRITER
REPLICATED PATTERN

WHAT IS CONTACT?

- PERFORMANCE AS FUNCTION OF SURFACE
VELOCITY & USAGE

Classification of Optical Data Storage

	Read-Only	Read/Write	
		Write-Once	Erasable
Media Type	Factory replicated plastic disk with embossed surface	Various thin film metal or organic materials	Magneto-optic or phase-change thin film materials
Media Capacity Both Sides 30 cm Disk	1 hr continuous video 100,000 video frames 1 hr digital audio* 2-8 GB Data	2-8 GB Data 20K-100K A4 doc.	1-4 GB Data
Applications	Consumer entertainment Education/training Program distribution Database distribution Videogame ROM	Document storage Archival database (tape replacement) On-line mass storage (juke-box)	High capacity, low cost store for small systems
Media Cost (†)	\$2-10/GB	\$10-50/GB	\$10-50/GB
Drive Cost (†)	\$0.5-5K	\$5-20K	\$5-20K

* 12 cm disk, 1 side

† R. Durbeck IEEE MSS (1982)

General Requirements of Optical Data Storage Media

- High resolution and regular mark geometry
To achieve high data density with adequate SNR and BER
- No intermediate processing
To permit data verification during recording
- High sensitivity to diode laser wavelength, $<100 \text{ mJ/cm}^2$, 100 ns pulse
Low energy marking mechanisms
High optical efficiency — antireflection structures.
High thermal efficiency — low thermal diffusivity media
- High playback contrast for mark, $C \geq 0.2$
To minimize shot noise
- Well defined recording threshold
To permit repetitive read without degradation
- Archival stability of media and recorded data
- Compatible with formatted disk substrate
- Low cost/MB

ERASABLE OPTICAL STORAGE

- * MAGNETIC AND OPTICAL DENSITIES
BECOMING SIMILAR
- * DO NOT REALLY NEED OR WANT R/W CAPABILITY
FOR ARCHIVAL STORAGE
- * "UPDATE-IN-PLACE" OF GREAT VALUE FOR
DIRECT ACCESS TRANSACTION ORIENTED SYSTEMS
- * DIRECT ACCESS MEANS ON-LINE
- * IF REMOVABLE - SHOULD BE ARCHIVAL
- * WHAT THEN HAS ERASABLE OPTICAL TO OFFER TO
JUSTIFY A TECHNOLOGY CHANGE?

PERFORMANCE CHARACTERISTICS OF CRYSTALLINE PHASE-CHANGE MEDIA

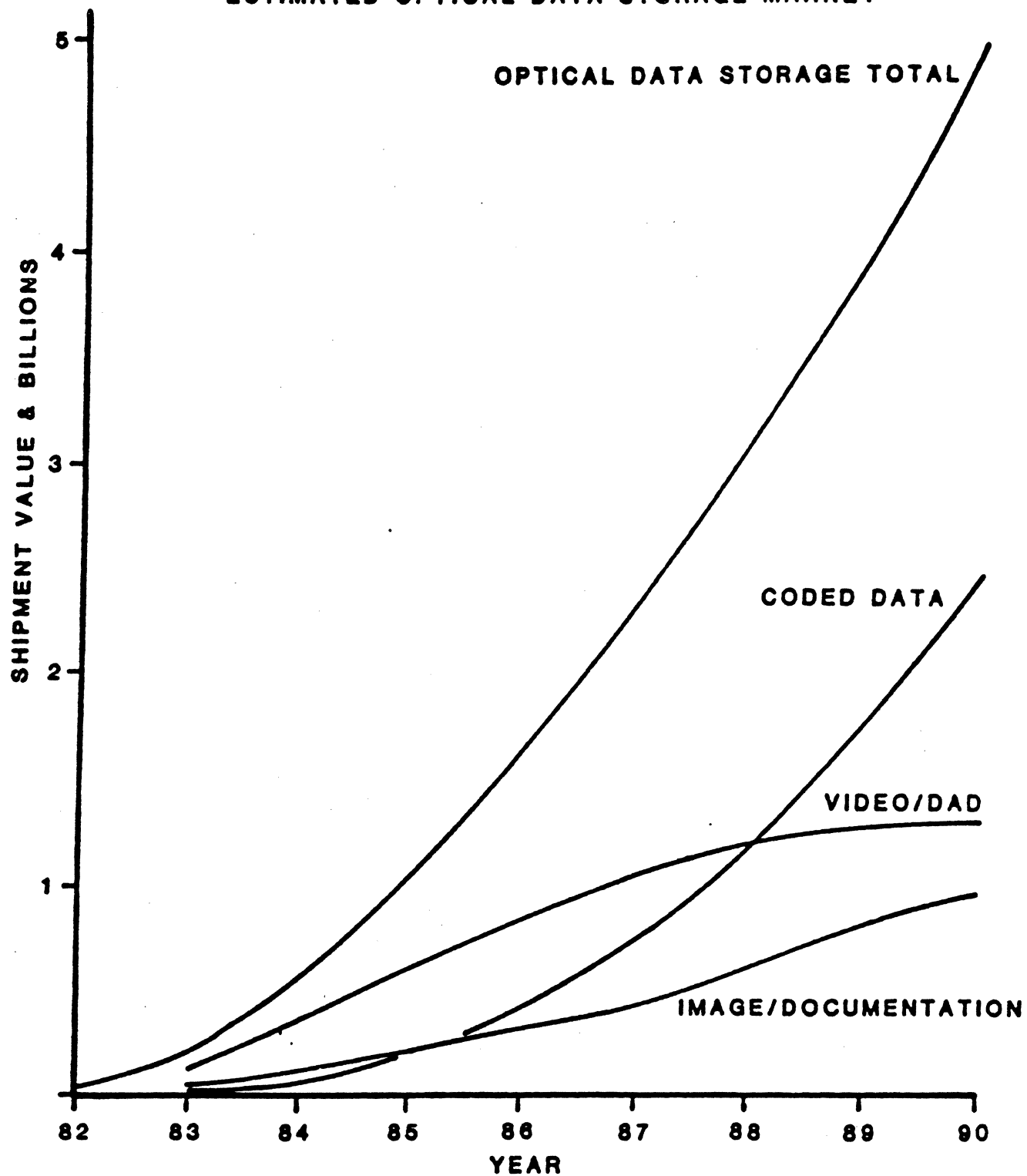
DISK ROTATION RATE	1800 RPM
DISK DIAMETER	20 CM
DATA RATE	1.25 MB/s
RECORD POWER	8MW
RECORD SPOT	0.8μ DIAMETER, λ = 830NM
ERASE POWER	10MW
ERASE SPOT	10μ X 1μ, λ = 780NM
PLAYBACK CNR	55DB (30KHZ NOISE BW)
NO. OF CYCLES	>10 ⁶

- - - - -

PERFORMANCE CHARACTERISTICS OF MAGNETO-OPTIC MEDIA

	SHARP	3M	MATSUSHITA
READ/WRITE WAVELENGTH	780NM	820NM	830NM
MEDIA	GDTBDYFE QUADRILAYER	- QUADRILAYER	GDTBFEGE BILAYER
DISK ROTATION RATE	900 RPM	1860 RPM	1800 RPM
DATA RATE	4 MB/s	16 MB/s	4 MB/s
RECORD POWER	4.8 MW	10 MW	9 MW
READ POWER	1.8 MW	1.5-3 MW	1.8 MW
PLAYBACK CNR (30 KHZ)	40 DB	50 DB	49 DB
NO. OF CYCLES	-	-	>10 ⁷

ESTIMATED OPTICAL DATA STORAGE MARKET



OPTICAL STORAGE IS A CURRENTLY EMERGING
PRODUCT CATEGORY OFFERING A VARIETY OF
FUNCTIONAL MODES: READ-ONLY, WRITE-ONCE AND
REVERSIBLE.

WITH THE EXCEPTION OF REVERSIBLE OPTICAL
STORAGE, IT CAN BE LARGELY COMPLEMENTARY TO
EXISTING MAGNETIC DISK TECHNOLOGY.

LOW COST REPLICATION OF HIGH CAPACITY OPTICAL
READ-ONLY MEDIA CD-ROM WILL PERMIT
SIGNIFICANT NEW APPLICATIONS IN IMAGE AND
DATA DISTRIBUTION.

HIGH CAPACITY, LOW COST, REMOVABLE WRITE-ONCE
OPTICAL MEDIA CAN ATTACK MAJOR NEW
APPLICATION AREAS WHICH ARE marginally (OR
NOT) BEING MET BY MAGNETIC STORAGE.

OTHER OPTICAL STORAGE ISSUES

- * REMOVABLE
 EXPECTATION OF BEING ARCHIVAL

- * ON-LINE USE
 THROUGHPUT
 ACCESSES/GIGABYTE
 MULTIPLE ACTUATORS?

- * BACKUP FOR HIGH CAPACITY
 READ/WRITE OR WRITE ONCE
 OPTICAL DISKS
 DRIVE & MEDIUM CONCERNS

CHANGING NATURE OF DATA STORAGE MARKETPLACE

*

COMMODITY MARKET

HIGH VOLUME
COST SENSITIVE

*

UNCONTROLLED ENVIRONMENTS

PERVASIVE USES

*

MAINTENANCE FREE

*

GROWING REQUIREMENT FOR COMPATIBILITY

- The User
 - Lowest cost/bit
 - Read/Write and nonvolatile
 - Competitive marketplace-large choice of product offerings
- The Manufacturer
 - Multi-billion dollar industry
 - Established production processes
 - Demand for capacity increases faster than storage density from technological progress—growing market
- R&D
 - Areal density still far from ultimate limits
 - Fairly well understood phenomenon
 - Reversible process—inherently stable

Measuring the Potential of Storage Technologies

- **Physical Limits — (Translation: Ultimate)**
- **Engineering Limits — (Translation: Feasible)**
- **Marketplace Limits — (Translation: Rubber meets the Road)**

Magnetics versus Optics

- **Issues**
 - **Archival Quality**
 - **Cost for Library Storage**
 - **Perception**

Actual Experience versus Benefit of the Doubt

COMPARISON OF CURRENT PERFORMANCE PARAMETERS IN MAGNETIC AND OPTICAL STORAGE

	IBM 3380	Optical	
Areal Density	12	200-600	Mb/in ²
Lineal Density	15	15-45	Kbpi
Track Density	~ 800	15	Ktpi
Data Rate	3	0.5-3.0	MB/s
Seek Time	16	85-500	ms
Access Density	~ 80	2-5	IO/s/GB

Ultimate Limits?

- **Magnetic Recording**
 - **Minimum Domain Size**
 - **Medium Signal to Noise Ratio**

Spacing Dominant Parameter

- **Optics**
 - **Limits due to Wavelength of Light**

ARCHIVAL STORAGE

(MEDIA TRANSPORTED TO READ/WRITE DEVICE)

MARKET ISSUES THAT AFFECT TECHNOLOGIES

* SOURCE OF DATA

- DATA RATE
- ACCESS NEEDS
- COST OF "DEAD" STORAGE

* INCLUDES MANY NEW APPLICATION AREAS

- NO COMMITMENT TO EXISTING TECHNOLOGY

* DEFINITION OF "LIFETIME"

- DATA AVAILABLE FOR EXTENDED BUT INDEFINITE NUMBER OF YEARS
- AGING PHENOMENA
- TAMPERPROOF

MAGNETIC VERSUS OPTICAL TECHNOLOGY

CONSENSUS EMERGING

- * NO GREAT DIFFERENCE IN DENSITIES
EXPECTED FOR ON-LINE STORAGE;
THUS,
TIME LEAD OF OPTICS (DENSITY-WISE)
ONLY FEW YEARS AT BEST.

CONCLUSION

- * MARKETPLACE MOST CRITICAL ASPECT FOR
SUCCESSFUL INTRODUCTION OF
OPTICAL STORAGE.
- * REMOVABILITY IN A DISK FORMAT
AN ESSENTIAL ATTRIBUTE FOR SUCCESS
(DIRECT ACCESS WHEN ON DEVICE)

MEDIA REMOVABILITY

DISK VERSUS TAPE

FOR BACKUP -- WANT SECOND COPY

FOR LOW COST/MBYTE FOR ARCHIVAL STORAGE NEED SHELF STORAGE

(DISK OR TAPE CARTRIDGE)

FOR REASONABLE ACCESS TO SHELF STORAGE NEED AUTOMATIC LIBRARY

AUTOMATIC LIBRARY REQUIRES MORE THAN ONE PATH TO DATA

FOR RELIABILITY

ACCESS TO DATA THEN IS FUNCTION OF LIBRARY AS WELL AS

STORAGE MEDIUM

DATA ORGANIZATION KEY AND THIS RELATES TO READ & WRITE FEATURES

ARCHIVAL LIBRARY

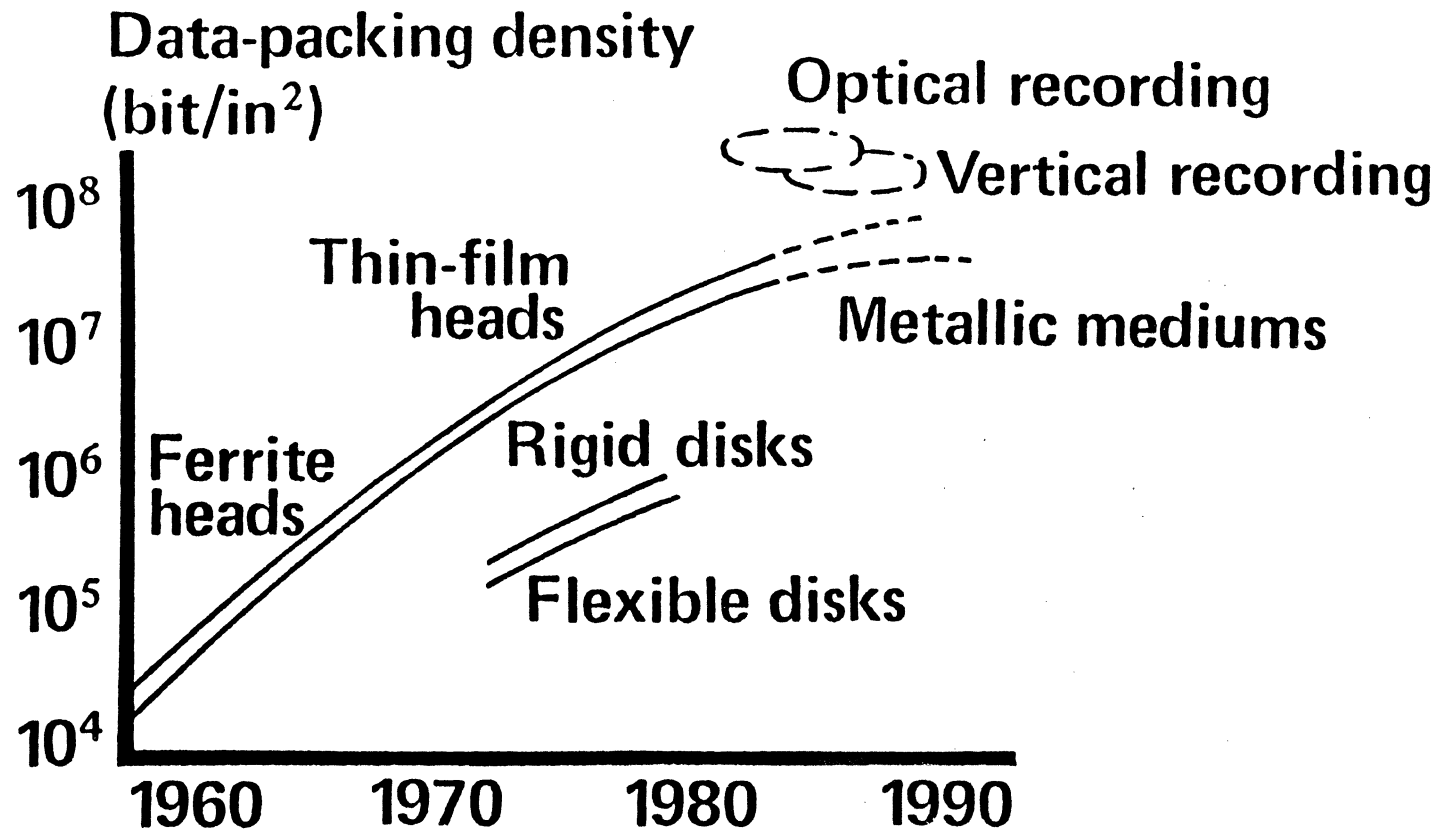
OPTICAL DISK VS HIGH DENSITY MAGNETIC TAPE

- * COST PER MEGABYTE - FAVORS MAG TAPE
- * DATA RATE - FAVORS MAG TAPE
- * VOLUMETRIC EFFICIENCY - FAVORS MAG TAPE
- * LIBRARY CONFIGURATIONS - FAVORS MAG TAPE
- * ACCESS TO MEDIUM UNIT - FAVORS MAG TAPE
- * ACCESS WITHIN MEDIUM UNIT - FAVORS OPTICAL DISK
- * ARCHIVAL LIFE - FAVORS (?)

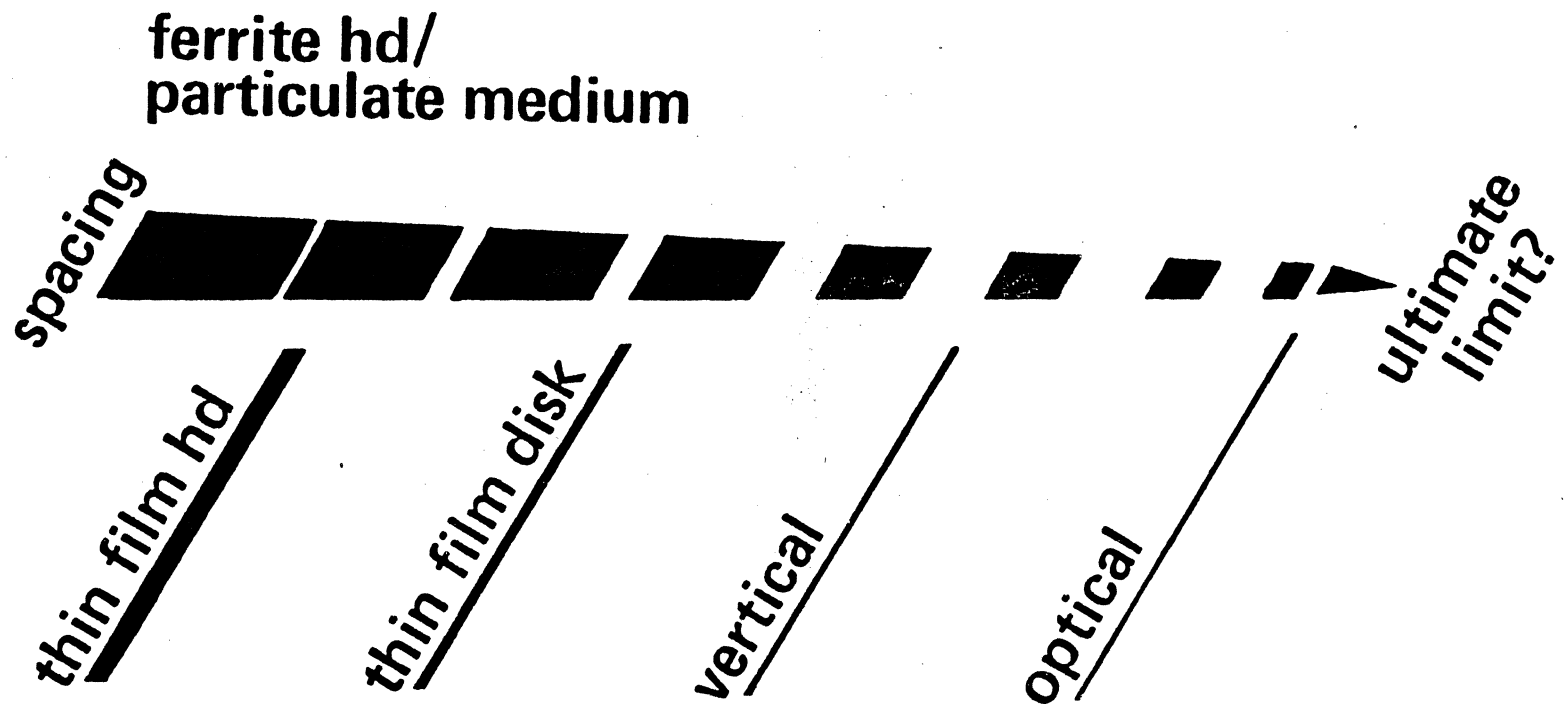
APPLICATION KEY TO

DISK VERSUS TAPE IMPLEMENTATION

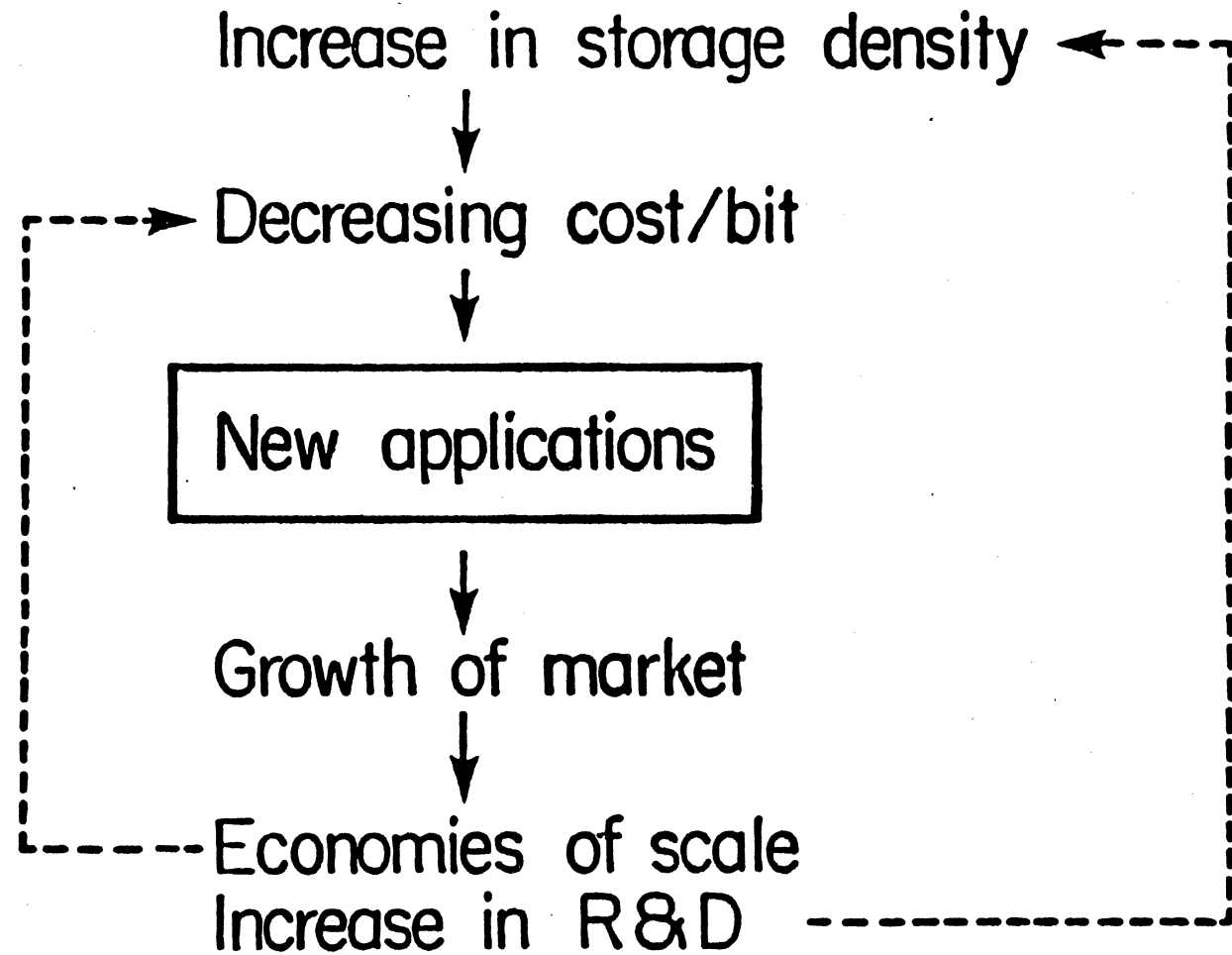
Increase in Areal Density with Time



The Moving Target



Mass storage



REFERENCES

1. IBM DISK STORAGE TECHNOLOGY (SAN JOSE, 1980), AVAILABLE FROM IBM AS ISBN 0-933186-02-9.
2. INTRODUCTION TO IBM DIRECT ACCESS STORAGE DEVICES, MARILYN BOHL, SCIENCE RESEARCH ASSOCIATES (CHICAGO, 1981). ISBN 0-574-21140-3.
3. ALAN E. BELL, "CRITICAL ISSUES IN HIGH-DENSITY MAGNETIC AND OPTICAL STORAGE" - PART 1, LASER FOCUS, AUG 83, PP 61-66.
4. ALAN E. BELL, "CRITICAL ISSUES IN HIGH-DENSITY MAGNETIC AND OPTICAL STORAGE" - PART 2, LASER FOCUS, SEP 83, PP 125-136.